



## Transfer and Reuse of Knowledge from the Service Phase of Complex Products

Vianello, Giovanna

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# Transfer and Reuse of Knowledge from the Service Phase of Complex Products



**PhD thesis 14.2011**

**DTU Management Engineering**

Giovanna Vianello  
October 2011

TECHNICAL UNIVERSITY OF DENMARK

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Ph.D. thesis

**Giovanna Vianello**

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Transfer and Reuse of Knowledge from the Service Phase of Complex Products

PhD thesis

Giovanna Vianello

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DTU Management Engineering

Institut for Planlægning, Innovation og Ledelse

Produktionstorvet 424

2800 Lyngby

Tel: +45 4525 4800

E-mail: [phd@man.dtu.dk](mailto:phd@man.dtu.dk)

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# Abstract

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The reuse of knowledge generated during the different phases of a product's lifecycle is crucial for a company in order to achieve competitive advantage. This thesis investigates knowledge transfer within the service phase and between service and design phases through case studies from the oil industry. Knowledge generated during the service phase was analysed from the point of view of service engineers and engineering designers. Furthermore, the mechanisms involved in the transfer of knowledge within the service phase and between service and design were investigated. Both service engineers and engineering designers were interested in knowledge about changes, issues and improvements generated during service; however, engineering designers were more orientated towards knowledge of the equipment at a component level while service engineers were interested in obtaining an overview of the systems. The study showed that knowledge transfer between the service and design departments was not systematic and consisted primarily of knowledge pushed by service engineers to engineering designers. The issues that posed a barrier to a systematic reuse of service knowledge were taken into consideration whilst developing a model for managing the knowledge generated during the service phase. The core of this model, called the RSK model, is the analysis phase, in which information from service cases is evaluated and integrated into existing documentation. The RSK model has been developed based on the case studies from the oil industry, however an auxiliary case study from the aerospace industry indicated it is also suitable to answer the needs of the variant design industry.



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# 1. Introduction

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An emerging trend in engineering design is to consider issues regarding different phases of the product lifecycle during the design of a new product. Knowledge from the later phases of the lifecycle and its feedback to the design phase is important for the success of a product as the transfer of operational experience to engineering designers facilitates the correction of product flaws and suggests directions for future improvements. An effective reuse of operational experience and a systematic learning from past cases require a company to adopt a suitable knowledge management strategy, designed considering the characteristics of the product in question, the structure of the organisation and the service provided. Moreover, as many manufacturing companies are moving their business strategy from simply selling products to also servicing them throughout their lifecycle, it is equally relevant to reuse the experience from service within the service phase itself, in order to improve the quality and the consistency of the service provided.

Despite the fact that companies are now aware of the value of knowledge generated throughout a product's lifecycle and tend to capture and store a vast portion of it into repositories, a complete understanding of how to effectively reuse this knowledge and turn it into a factor of competitive advantage is still needed.

This thesis describes a PhD project that focused upon understanding how to facilitate the reuse of the knowledge generated during the service phase of complex products, which are characterised by a high number of components with complex interactions between each other and a certain degree of novelty. The research project followed a case study approach and two companies from the oil industry, (1) a supplier of drilling equipment and (2) a drilling contractor, were selected as main case studies. The supplier of the equipment was involved throughout the lifecycle of the equipment by providing service in the form of repair, training, maintenance, spare parts and overhaul; whilst the drilling contractor defined the equipment specifications and

operated it. Both the companies perceived the reuse of knowledge from the lifecycle of the equipment as critical for their competitiveness as it was necessary for continuously improving both the design of the equipment and the processes that characterised service and operation. Literature suggests that this can be achieved in multiple ways: by the reuse of available documentation, with knowledge managed through information and communication technologies (McMahon, Lowe et al. 2004) or through personal communication within and across organisations, by, for example, building personal networks amongst employees (Wenger 2000). During the research project, case studies from the collaborating companies were analysed in order to understand the mechanisms characterising the transfer of knowledge from service and propose a model for managing knowledge that is suitable for supporting the reuse of service knowledge. Subsequently, the proposed model was validated against an auxiliary case study from the aerospace industry.

The project was conducted during a four year period, between 2007 and 2010, at the Technical University of Denmark, Product Development Section, and was jointly funded by the Technical University of Denmark and Aker MH ASA.

## **1.1 Motivation**

The initial idea of the research project arose from a dialogue with industry, namely a supplier of drilling equipment for the oil industry, that highlighted difficulties in reusing knowledge emerging throughout a product's lifecycle. These difficulties in reusing knowledge were in contrast to the large amount of information available and the time spent capturing it into documentation, suggesting that an inappropriate knowledge management strategy had been adopted.

The importance of investigating the topic was also supported by research studies indicating that the issues related to not being able to use and take advantage of available information were common in industry, and not limited to the specific company. For instance, there was general agreement in seeing information overload as one of the most critical problems companies have had to face in the last decades (Toffler 1984).

This phenomenon, which was first described in the 1960s (Gross 1964), has gained increasing importance with the diffusion of the Internet. General causes of information overload include:

- Increasing amount of new information continuously made available;
- Ease of transmitting data through the internet.
- Variety of channels available for transferring information (e.g. telephone, e-mail, messages, databases).
- Large amounts of historical information stored in repositories.
- Contradictions and inaccuracies in available information.
- Lack of a method for comparing and processing different kinds of information.
- Pieces of information unrelated or lack of any overall structure to reveal their relationships.
- Inappropriate knowledge management methods and tools

The dialogue with industry highlighted that the tendency of not reusing the information stored in a company's repositories was particularly evident for information from the service phase: information that was generated during this phase of a product's lifecycle was captured in a variety of forms; however this information seemed to be scarcely reused both within service and during the design phase. Hence, this motivated the research project's specific focus upon knowledge arising from service. A further motivation for researching on how to improve the reuse of knowledge from service was the growing interest of practitioners and researchers in engineering design for the opportunities that could derive from a different approach towards service. In this context, an effective way of capturing and reusing knowledge from service was crucial to improve the in-service support provided and align it, as well as the product, to the market's needs.

## **1.2 Aims**

The research project aimed to facilitate the reuse of knowledge from the service phase in order to support:

- Engineering designers, while designing complex products;
- Service engineers, while providing in-service support.

Therefore, the research object of this project was technical knowledge from the service phase, as perceived from two different perspectives: the point of view of engineering designers and that of service engineers. The research project is composed of two parts. The first part of the research (descriptive study) aimed to understand the characteristics of knowledge from service and how this knowledge was transferred and reused within service and across departments; this investigation was based upon case studies from industry. The second part of the project (prescriptive study) focused upon proposing a model for managing service knowledge and facilitating its systematic reuse.

The researcher expected that differences in knowledge needs between engineering designers and service engineers emerged from the case studies and that these differences represented a barrier for transferring knowledge from service to design. The investigation of industrial practice that was conducted in the first part of the research project aimed to identify these differences and other issues that impeded knowledge reuse and overcome them through a suitable knowledge management strategy.

### **1.3 Research questions**

The set of research questions addressed in the first part of the research project (descriptive study) aimed to improve the understanding of characteristics of the knowledge arising from the service phase of complex products and how it is transferred and reused. The specific questions addressed during the study are listed below.

*RQ.1 What characterises the knowledge arising from the service phase of complex products? What aspects of knowledge from service are relevant for service engineers and engineering designers?*

This set of questions aimed to better define the research object that was investigated during the project and understand how the two actors taken into consideration, service



engineers and engineering designers, perceived it. The results are presented in Chapter 4.

*RQ.2 How is knowledge from service transferred within the service phase and across phases of the lifecycle?*

This question aimed to investigate the knowledge transfer mechanisms that were adopted for transferring knowledge within service and across the phases of the product's lifecycle. The results are presented in Chapter 4.

The second part of the research project (prescriptive study), which focused upon developing a strategy for knowledge management to support the reuse of knowledge from the service phase of complex products, aimed to answer the research question:

*RQ. 3 How can the current situation be improved in order to obtain a systematic reuse of knowledge from the service phase of complex products?*

The nature of this question is different compared to the first two questions, as its aim was to understand how to improve the current situation, specifically in respect to the reuse of knowledge from the service. The results are presented in Chapter 5.

## **1.4 Research contributions**

This research aims to contribute to research in the field of engineering knowledge management by identifying the characteristics of knowledge generated during the service phase of complex products and proposing a model to support its reuse, both within service and across phases of a product's lifecycle.

## **1.5 Key terms**

This section illustrates the key terms that have been used throughout the thesis, and clarifies their meaning and use within the context of this research.

### **1.5.1 Service and service phase**

Despite general agreement on the importance of *service*, the definition of what service actually is varies from case to case, as different approaches towards it have been

adopted in literature and in practice. Several research studies focused upon how to design *services* concurrently to products, or instead of products (Alonso-Rasgado et al. 2004). Other approaches focused upon how to support a product throughout its lifecycle in order to maintain or regain its functionalities (Long, et al. 2009). This latter type of approach towards service is the one adopted by the research project.

The term *service phase* is used in the thesis to indicate the part of the lifecycle when service engineers were involved; whilst the term *service* covers installation, upgrading, maintenance, software support and training. This definition of *service* is in line with the approach towards service adopted in other research on complex products (Hobday 1998).

### 1.5.2 Engineering designers and service engineers

The two key actors taken into consideration in the research study were:

- Engineering designers (and project managers)
- Service engineers (and operators).

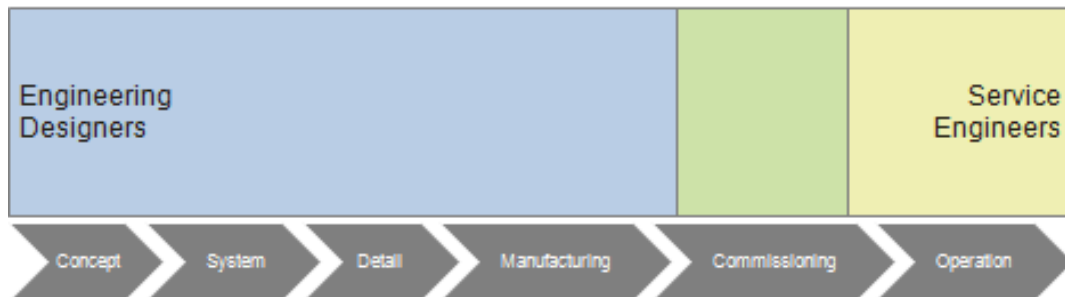


Figure 1.1 Engineering designers and service engineers in relation to the product lifecycle.

In the main case study, which focused on the supplier of drilling equipment, engineering designers were involved throughout the development process from the definition of the requirements in the conceptual phase to the starting of the operational phase; while service engineers were involved from the commissioning and installation phase towards the operation phase by providing a broad range of in-service support (see Figure 1.1). The handover from engineering designers to service engineers occurred during the commissioning phase when both the groups were involved in

testing components and systems, first at the company's warehouse and later at the shipyard.

In the case study based on the drilling contractor, project managers were the main actors during the development phases, from concept development to commissioning; after that phase operators and rig managers took over.

During this research project, the knowledge transfer across phases of the lifecycle was analysed comparing the main actors of the development phase, engineering designers and project managers, to the actors of the service phase, namely service engineers and operators.

### **1.5.3 Knowledge, information, data**

Several research domains approached *knowledge* by defining the differences between *knowledge*, *information* and *data* (see also Chapter 3, where a comprehensive review is undertaken), however this distinction has limited practical implications. In this thesis, a more pragmatic approach was adopted, as suggested by VonKrogh et al. (2001): the term *knowledge* includes both explicit and tacit elements, while *information* is used interchangeably with codified knowledge and is referred to documentation.

## **1.6 Background knowledge on the main case study**

### **1.6.1 Supplier of drilling equipment**

The main case study analysed was a company supplying drilling systems for the oil industry. The company, a subsidiary of a group with interests in different aspects of the energy sector, had grown exponentially in the last ten years, following a trend common in the oil business. Around 2000 were employed by the company at the time of the study. The last years were characterised by a shift in the nature of the systems provided, that moved from mainly mechanical to more complex mechatronics systems (see Figure 1.2), and by a constant growth, that made the capability of recruiting qualified people critical for the success of the company. This resulted in a broader range of expertise required while designing and servicing the products and difficulties

in obtaining a complete understanding of the product's functionalities, particularly at the operator's side.

The drilling systems developed by the company covered the complete range of equipment necessary for an offshore oil rig to operate and were designed-to-order, based upon client's requirements. Most of the equipment was developed by modifying the standard design in order to take into account the characteristics of the rig (e.g. expected performances, lay-out, size), the preferences of the client, and the expected field of operation. Due to the customized nature of the equipment, prototyping and testing were not part of the development phase. The equipment was developed in a linear manner without major iterations and tested at the testing facilities only after being manufactured. Additional testing was carried out on the rig during the installation and the commissioning phases to verify the functioning of the whole system and the various sub-systems in an operative context.

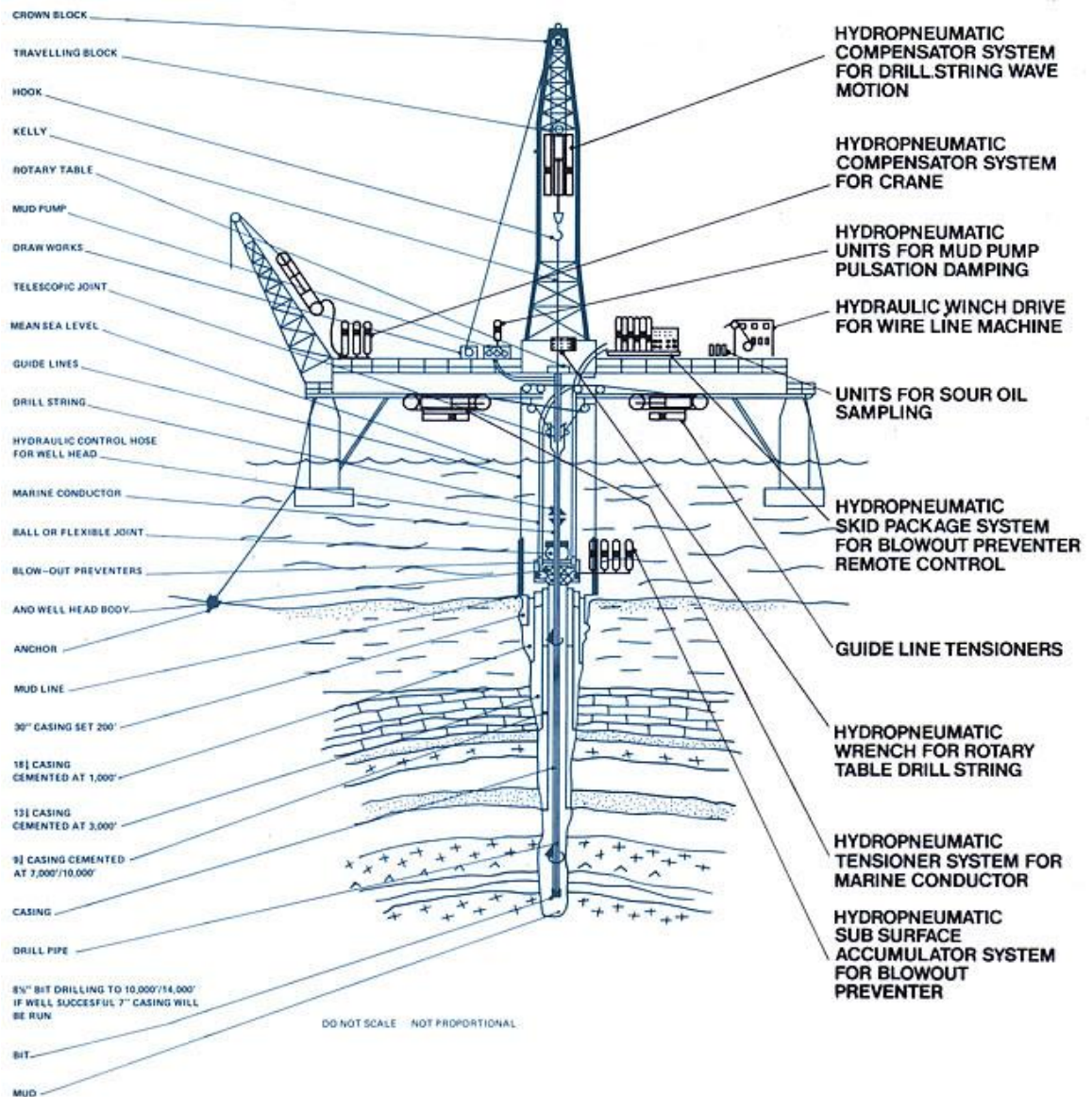


Figure 1. 2 Scheme of an offshore drilling rig and its equipment (from <http://www.mediasteed.com/2010/04/01/open-season-on-offshore-drilling/>)

### 1.6.2 In-service support provided

The company was involved throughout the entire lifecycle of the equipment: from developing a concept to supporting the operators during the service phase (e.g. providing maintenance, repair, training, overhaul, spare parts, upgrades). A dedicated department was established with full responsibility for supporting the equipment when it enters service. Service engineers were generally involved in a service case by

physically being sent on the rig and implementing the selected solution, while senior service engineers were in charge of managing the in-service support from the headquarters and providing service engineers with the description of the work to be performed and guidance during the service job. A customer support unit was set up as an initial single point of contact between the company and the client for any type of inquiry.

### **1.7 Structure of the thesis**

Figure 1.3 provides an overview of the structure of the thesis and lists the topics that are covered in each chapter.

Chapter 2 describes the methodology adopted for conducting this research project, from the paradigms representing its framework to the methods chosen to investigate the case studies.

Chapter 3 presents the literature survey on the research fields that are relevant for the project and describes how existing literature helps answer the three research questions.

Chapter 4 describes the descriptive study based on the case studies from the oil industry and discusses how the findings for the analysis of the case studies answer the first two research questions.

Chapter 5 answers the third research question by identifying the issues that impede the reuse of knowledge from service and proposing a model to facilitate a systematic reuse of service knowledge. The internal and external validity of the proposed model are evaluated in Chapter 6 through a workshop conducted at the collaborating company and an auxiliary case study from the aerospace industry.

Finally, the implications of the research project for industry and academia are discussed in Chapter 7 and the conclusions are drawn in Chapter 8.

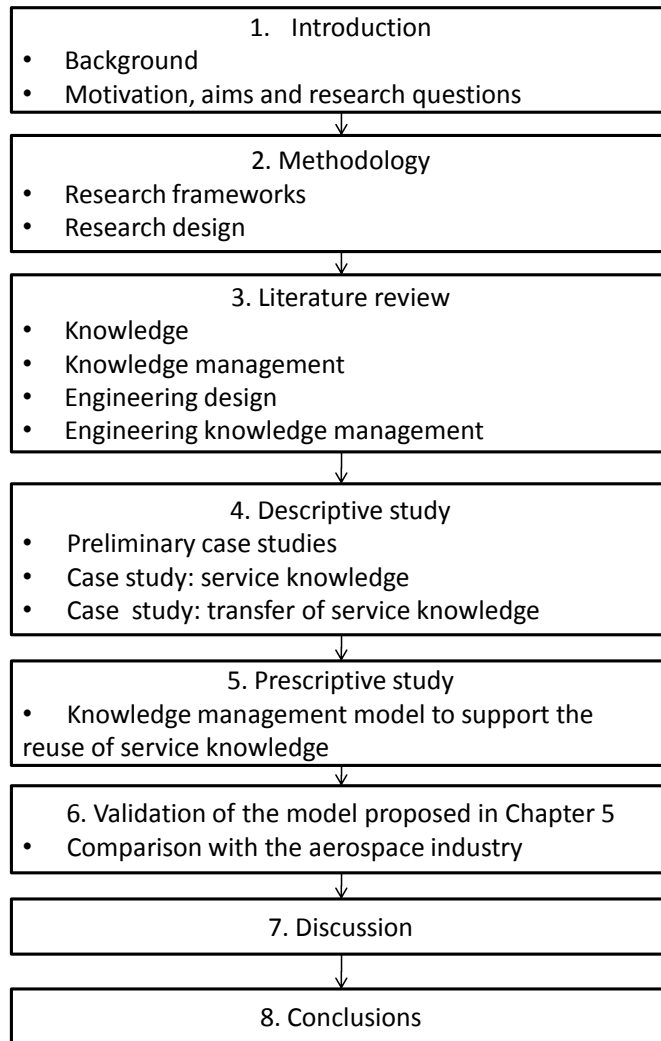


Figure 1.3 Structure of the thesis.

## 1.8 Summary

This introductory chapter identified the need for companies to improve the reuse of knowledge, particularly when it is generated during service, as the main motivation behind this research project and formulated the three research questions that will be answered through this thesis. They are:

*RQ.1 What characterises the knowledge arising from the service phase of complex products? What aspects of knowledge from service are relevant for service engineers and engineering designers?*

RQ.2 *How is knowledge from service transferred within the service phase and across phases of the lifecycle?*

RQ.3 *How can the current situation be improved in order to obtain a systematic reuse of knowledge from the service phase of complex products?*

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## 2. Methodology

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### 2.1 Introduction

This chapter illustrates the research approaches that were adopted during the research study. They are described at three levels: research frameworks, research methodology and research methods. Section 2.2 defines the concept of research framework, as adopted in this study, and describes the research frameworks that represent the foundation of the project. Sections 2.3 to 2.6 illustrate the sequential phases constituting the research project. Methodology and methods adopted in each of the phases are illustrated in the related subsections.

### 2.2 Research paradigms and frameworks

*A paradigm represents a philosophical and theoretical framework of a scientific school or discipline within which theories, laws, and generalisations and the experiments performed in support of them are formulated.* (Merriam Webster Online Dictionary).

Research paradigms have a different role in the physical and the social sciences, as in the physical sciences only one paradigm is valid at a time, whilst in the social sciences several paradigms may coexist. These two approaches towards research paradigms are discussed in the following paragraphs.

#### ***Paradigms in the physical sciences***

According to Kuhn, the progress of knowledge in the physical sciences follows two distinguished processes (Kuhn 1970):

- Within normal science: scientists work on the incremental understanding of a scientific phenomenon, grounded upon previous studies, without challenging or testing the underlying assumptions describing the phenomenon.
- Through a paradigm shift: a change in basic assumptions of a research domain occurs.

Once a paradigm shift is complete, a scientist cannot build his theory upon past paradigms that have been contradicted by the one in use, as old paradigms are not suitable to explain new findings.

Shifts in paradigms have characterised scientific revolutions in various domains; examples of paradigm shifts are:

- The transition between Newtonian Physics and Einsteinian Relativism.
- The acceptance of Charles Darwin's theory of natural selection replacing the previous evolutionary theories.
- The transition from Ptolemaic cosmology to a Copernican one.

### ***Paradigms in the social sciences***

The applicability of the concept of paradigm to the social sciences has been questioned by various scientists as, in contrast to the physical sciences, the social sciences are characterised by the coexistence of different frameworks and the absence of theoretical consensus. As Kuhn wrote:

*“Unlike a normal scientist, a student in the social sciences has constantly before him a number of competing and incommensurable solutions to problems, solutions that he must ultimately examine for himself.”* (Kuhn 1970).

Consequently, a social scientist can choose among an array of frameworks, which may be more or less common during any given period, yet all legitimate. The coexistence of various frameworks in the social sciences led Kuhn to state that the concept of paradigm can be only applied to the physical sciences. Mattei Dogan (Dogan 2001) confirmed Kuhn's argument and linked the absence of paradigms to the fact that the different schools of thought are mutually ignoring each other (polysemic concepts).

A broader approach towards the concept of research paradigms, which is adopted by other scientists, admits the existence of paradigms also in the social sciences. According to this approach a paradigm expresses the point of view of the scientist towards a research topic (Guba, Lincoln 1994); hence the term “paradigm” is used to

describe the set of experiences, beliefs and values that affect the way an individual perceives reality and responds to that perception. According to this approach, a "paradigm shift" in the social sciences denotes a change in how society perceives reality. A "dominant paradigm" refers to the values, or system of thought, that are widely accepted at a given time. Dominant paradigms are shaped both by the cultural background of a community and by the context of the historical moment. In order for a framework to become an accepted dominant paradigm, external support is essential. This support can be manifested through, for example, dedicated journals and conferences, professional organisations adopting the paradigm, and government agencies giving credibility to the paradigm.

### ***Implications for the research***

As the research presented in this thesis focused upon knowledge and its transfer mechanisms, the approaches adopted were mostly taken from the social sciences, despite the project being carried out in an engineering domain. In order to avoid the ambiguity that could derive from using the term paradigm in a project that ranges across social and physical sciences, the following sections of the thesis will refer to the paradigms that are from the social sciences as frameworks.

As no comprehensive theories have been developed in the field of engineering design with regard to knowledge transfer, the researcher searched for suitable frameworks from other fields, in order to provide theoretical foundations to the project. A survey across the different disciplines (e.g. organisational science, sociology, psychology, management, etc.) found a range of disjointed theories that were difficult to relate to each other, confirming Dogan's statement that social sciences are characterised by the coexistence of polysemic concepts (Dogan 2001).

The concept of knowledge economy was found to be the common driver for researching on knowledge management across the different disciplines. This concept was also identified as the overall research framework motivating the research project, and is described in detail in the following section, together with other relevant frameworks.

### **2.2.1 Research frameworks**

This section describes the frameworks that constitute the foundations of this research project.

#### ***Knowledge economy***

Research studies on knowledge and knowledge management from different disciplines share the underlying concept that we live in a knowledge economy, where knowledge is used to produce economic benefits as well as job creation (Drucker 2008). In this context, knowledge resources such as know-how and expertise are considered as critical as other economic resources. Disciplines such as economics, computer science, software engineering, mathematics, as well as psychology and sociology have adopted knowledge economy as a research framework and agree on the concept that improving the use of a company's internal knowledge leads to economic advantages. The same framework constitutes the foundation of the research study presented in this thesis.

The frameworks describing knowledge and knowledge management developed by the different disciplines and schools under the overall common framework of the knowledge economy are described in Chapter 3.

#### **Knowledge acquisition**

Frameworks describing what constitutes knowledge and how knowledge is acquired have multiple implications for this research project and influenced the design of the research project itself. They illustrate how knowledge is generated, (e.g. knowledge is created a priori, if knowledge is generated through intellectual constructs, or a posteriori, if knowing occurs through experience) and influence the interpretation of phenomena like knowledge acquisition and knowledge transfer that are the specific interests of the research project.

The investigation on how knowledge is acquired covers issues concerning the creation of knowledge, its proof and its transfer. Throughout the centuries different approaches

to knowledge acquisition led to the formulation of various frameworks. Some of the most significant among these are:

- *Empiricism*. Knowledge is empirical; it has to be justified through experience based on perceptual observation.
- *Rationalism*. Knowledge is innate and acquired by a priori processes.
- *Constructivism and pragmatism*. Knowledge is contingent and based on subjectivity.
- *Positivism*. The only authentic knowledge is scientific knowledge acquired by following the scientific method.

A detailed analysis of the implications of the mentioned theories is beyond the scope of the research project; nonetheless the overall approach adopted in the research is influenced by empirical and pragmatic theories on knowledge creation, as the investigation of knowledge and knowledge transfer carried out is grounded upon empirical evidence.

### **Design research methodology**

Research projects can be distinguished according to their purpose into (Blessing, Chakrabarti 2009):

- Projects that aim to investigate and understand a phenomenon or event;
- Projects that aim to propose guidelines, methods or tools to improve current practice by moving from the existing situation into a more desirable one.

The latter approach has been adopted in this research project, i.e. a pragmatic approach towards research, in agreement with the methodology for research into engineering design (DRM) proposed by Blessing and Chakrabarti (2009) and described in more detail in the following section.

The DRM was developed based upon the assumption that design research not only aims at understanding the phenomenon of design, but also at using this understanding in order to change the current situation.

The DRM describes an iterative process to be applied when conducting engineering design research; the phases constituting this process are illustrated in Figure 2.1 and described below. How each phase of the framework was applied to this research project is described in Sections 2.3 to 2.6.

The first phase of a research project is the identification of a set of criteria assessing the success of the project based upon the chosen research frameworks and assumptions related to the specific case. The success criteria have to be linked to lower level, measurable criteria (*criteria stage*). For instance, if the overall success criterion is to improve the design of a product, the derived measurable criterion could be related to the reduction of the number of failures or the increase of its performances during operation.

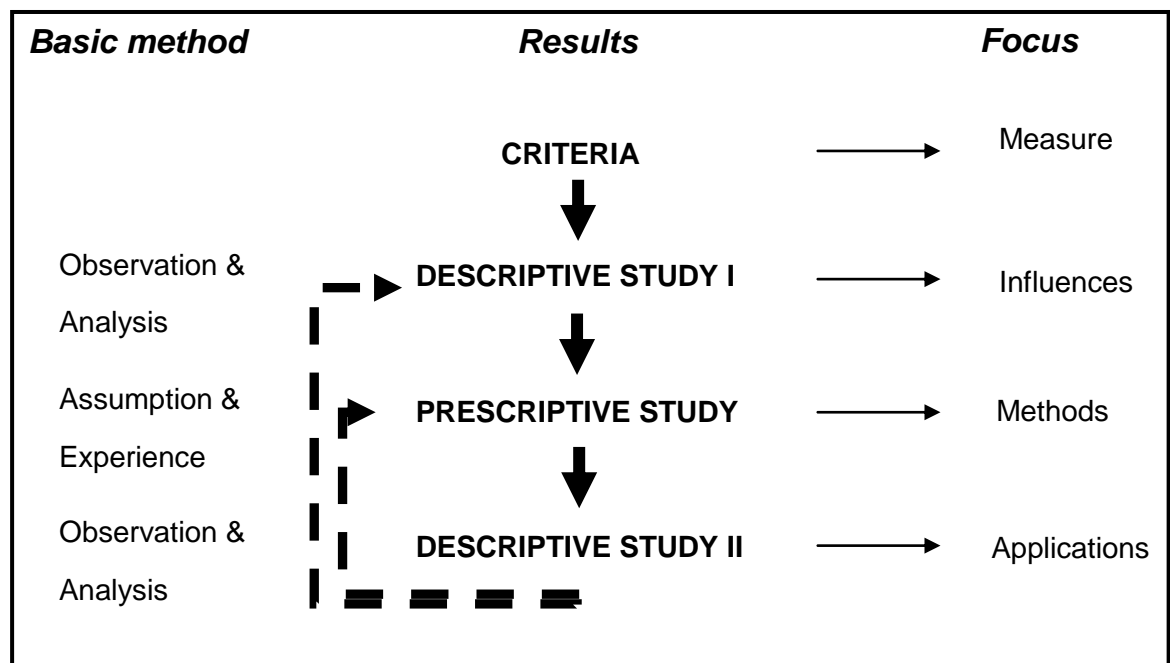


Figure 2.1 Design research methodology (Blessing, Chakrabarti 2009)

During the Descriptive Study I (*DSI stage*) the selected research objects are investigated in detail and the variables influencing them are identified. Once the relevant variables have been identified, the Prescriptive Study (*PS stage*) identifies the causal inferences and suggests directions for improvements by proposing models, tools, etc. to improve the current situation. The progress of a research project through the investigation of the chain of influencing factors is summarised in Figure 2.2.

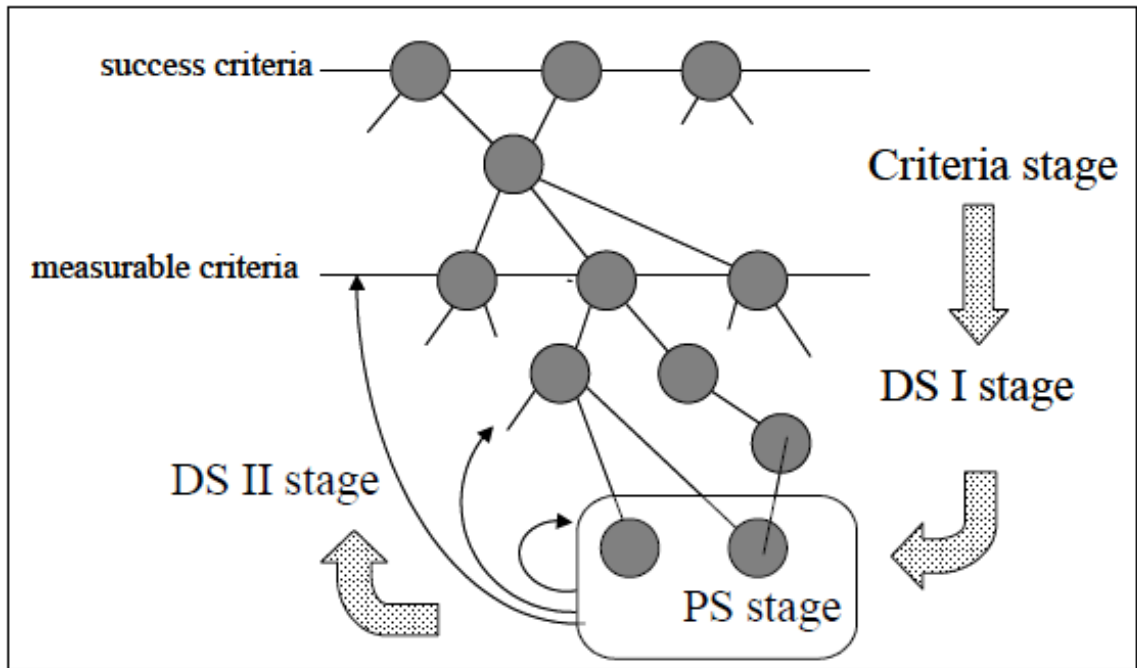


Figure 2.2 The network of influencing factors.

The validation of the proposed directions for improvement is conducted in the subsequent Descriptive Study (*DSII stage*). The iteration of descriptive and prescriptive phases results in a continuous refinement of the proposed solutions according to the success criteria initially chosen.

How the stages of the DRM have been applied to the research project is summarised in Figure 2.3 and described in detail in the sections to follow.

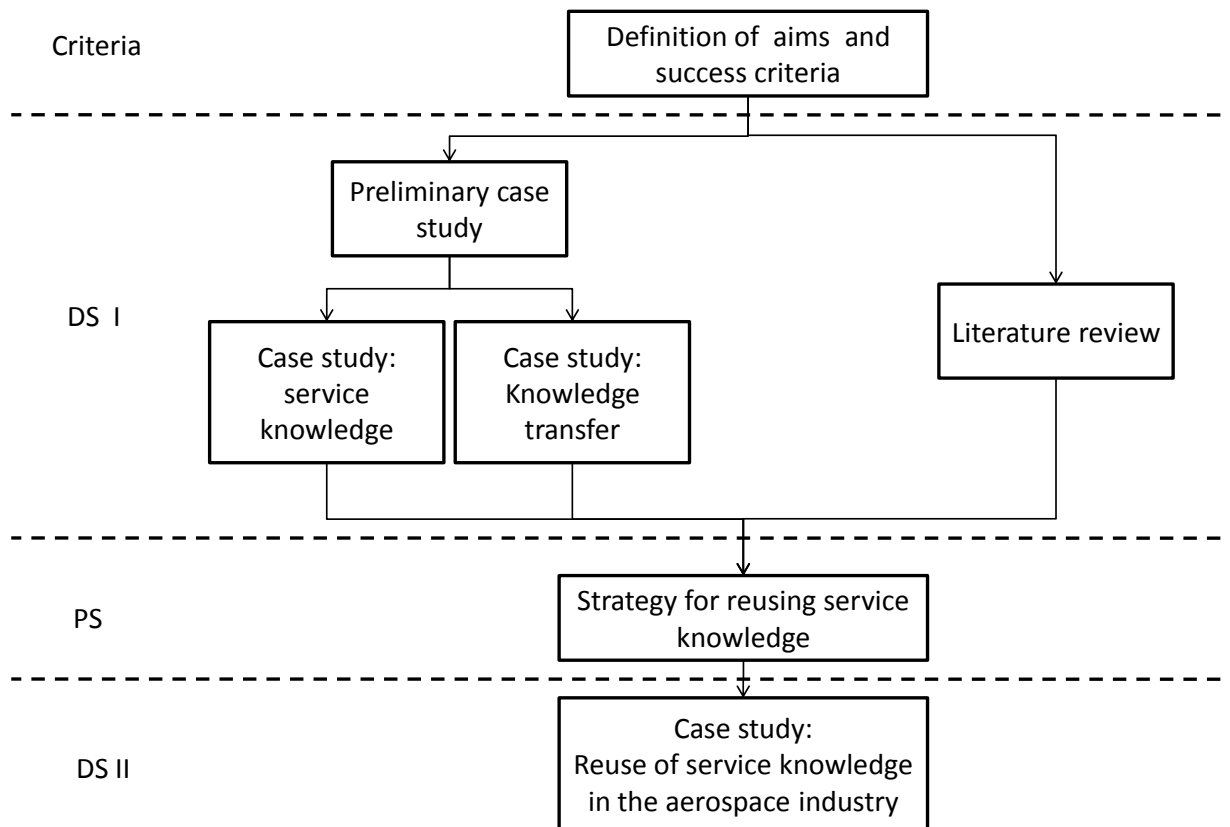


Figure 2.3 Stages of the research project, in line with DRM.

### 2.3 Success criteria

The research object that was investigated in this project is the knowledge from the service phase of complex products; the investigation was conducted with the aim of improving the reuse of this knowledge both within the service phase and across phases of the product's lifecycle. According to the knowledge economy framework, enhancing the ability of a company to reuse its internal knowledge positively impacts on its competitiveness. Specifically, advantages expected from a better reuse of knowledge from service include:

- Improving product quality (e.g. in terms of performance and reliability), by taking into account issues and ideas for improvements arising from products in operation during the development of the next generation of products.



- Improving the service support provided: e.g. by reducing time for handling service cases and achieving consistency across cases.

Hence these advantages can be seen as the success criteria of the project, and are expected to be met through a better reuse of knowledge from service. However, these criteria cannot be directly measured. Appropriate measurable criteria that allow verifying the increase in the reuse of knowledge are, for example, an increase of the number of documents retrieved or the reduction of recurrent errors in the equipment's design. The hypothesis behind this project is that designers' awareness of operational issues would enable them to take these issues into consideration during the development process, and, consequently, to design better products.

## **2.4 Descriptive study**

The descriptive study aimed to answer the first two research questions, already presented in Chapter 1.

*RQ.1 What characterises the knowledge arising from the service phase of complex products? What aspects of knowledge from service are relevant for service engineers and engineering designers?*

*RQ.2 How is knowledge from service transferred within the service phase and across phases of the lifecycle?*

### **2.4.1 Methodology**

The descriptive study was developed in two phases: (1) a literature survey, described in Chapter 3; and (2) three case studies that investigated industrial practice, that are described in Chapter 4.

The literature survey was carried out in order to obtain an overview of the state-of-the-art research in relevant fields and identify the factors to be taken into consideration while investigating the research object. This literature survey revealed that previous research did not provide enough detail on the phenomenon of the reuse of service knowledge in the engineering domain; subsequently, further evidence had to be collected. This was done through a series of case studies; the choice of a case

study approach against other possible approaches (summarised in Table 2.1) was motivated by:

- The tradition of research in engineering design, which commonly relies on case studies in collaboration with industry.
- The research questions characterising this project, which derived from the observation of issues common in industry but that have not been studied in depth in engineering design research.
- The nature of case study research, that allows multiple sources of data collection, such as surveys, interviews, archival analysis.

Table 2.1 Research approaches (Yin 1994)

<b>Strategy</b>	<b>Form of research questions</b>	<b>Requires control over behavioural events?</b>	<b>Focuses on contemporary events</b>
Experiments	How, Why	Yes	Yes
Survey	Who, What, Where, How Many, How Much	No	Yes
Archival analysis	Who, What, Where, How Many, How Much	No	Yes/No
History	How, Why	No	No
Case study	How, Why	No	Yes

Researchers in the engineering design field extensively collaborate with industry and base their research upon the analysis of case studies, as this strategy is suitable for investigating complex phenomena that are influenced by factors difficult to recreate in a fictional context (e.g. experiment) and obtaining insights on the motivation of the phenomena under investigation. An example of such a research project, based upon the collaboration between university and industry, is the KIM (Knowledge and Information Management) project, which involved 11 British universities and

industrial partners from a range of business sectors, including aerospace, construction, defence and healthcare (<http://www-edc.eng.cam.ac.uk/kim/>).

The choice of conducting case study research was also derived from the fact that the research object had not been studied in depth in engineering design research and there was a significant gap between general knowledge management theories and industrial practices. This research focused upon empirical case studies investigating the transfer and reuse of knowledge from service in an attempt to reduce this gap.

### ***Project development***

The case studies were developed according to the approach for building theories from case studies proposed by Eisenhardt (Eisenhardt 1989). Eisenhardt's approach was selected as it is appropriate for investigating research topics that are in their early stages, i.e. when studies are more grounded on empirical data than on previous literature. The process of building theories from cases is illustrated in Figure 2.4. The definition of research questions and aims has been covered in Chapter 1; the present chapter describes how the cases have been selected and what strategies were adopted for data collection and analysis, while the results from the case studies and their discussion are presented in Chapters 4 to 7.

Step	Activity	Reason
Getting Started	Definition of research question Possibly a priori constructs	Focuses efforts Provides better grounding of construct measures
Selecting Cases	Neither theory nor hypotheses Specified population	Retains theoretical flexibility Constrains extraneous variation and sharpens external validity
	Theoretical, not random, sampling	Focuses efforts on theoretically useful cases—i.e., those that replicate or extend theory by filling conceptual categories
Crafting Instruments and Protocols	Multiple data collection methods	Strengthens grounding of theory by triangulation of evidence
	Qualitative and quantitative data combined Multiple investigators	Synergistic view of evidence Fosters divergent perspectives and strengthens grounding
Entering the Field	Overlap data collection and analysis, including field notes	Speeds analyses and reveals helpful adjustments to data collection
	Flexible and opportunistic data collection methods	Allows investigators to take advantage of emergent themes and unique case features
Analyzing Data	Within-case analysis	Gains familiarity with data and preliminary theory generation
	Cross-case pattern search using divergent techniques	Forces investigators to look beyond initial impressions and see evidence thru multiple lenses
Shaping Hypotheses	Iterative tabulation of evidence for each construct	Sharpens construct definition, validity, and measurability
	Replication, not sampling, logic across cases	Confirms, extends, and sharpens theory
	Search evidence for “why” behind relationships	Builds internal validity
Enfolding Literature	Comparison with conflicting literature	Builds internal validity, raises theoretical level, and sharpens construct definitions
	Comparison with similar literature	Sharpens generalizability, improves construct definition, and raises theoretical level
Reaching Closure	Theoretical saturation when possible	Ends process when marginal improvement becomes small

Figure 2.4 Steps for developing case study research and building theories from cases (Eisenhardt 1989)

### 2.4.2 Case selection

The analysis of knowledge from service and its transfer focused upon complex products with the assumption that issues related to how to reuse knowledge are more critical for this type of product. Complexity has been first defined by Simon (1962) as characterised by:

- Hierarchy: that results in a product accessible at different levels: system, component, subcomponent;
- Near-decomposability: that is translated in parts connected to each other by loose links (e.g. interfaces);
- Alphabet: that is represented by a finite number of basic components constituting a product.

Table 2.2 Differences between complex and simple products (Hobday 1998)

	<b>Complex Product/System Project Organisation</b>	<b>Simple Products/ Mass Production</b>
<b>Product characteristics</b>	Complex component interfaces Multi-functional High unit cost Products cycles last decades Many skill/knowledge inputs (Many) tailored components Upstream, capital goods Hierarchical/systemic	Simple interfaces Single function Low unit cost Short product life cycles Fewer skill/knowledge inputs Standardised components Downstream consumption goods Simple architectures
<b>Production characteristics</b>	Project/small batch Systems integration Scale-intensive, mass production not relevant	High volume, large batch Design for manufacture Incremental process, cost control central
<b>Innovation processes</b>	User-producer driven Business to business Highly flexible, craft based Innovation and diffusion collapsed Innovation paths agreed <i>ex-ante</i> among suppliers, users etc. People-embodied knowledge	Supplier-driven Business to consumer Formalised, codified Innovation and diffusion separate Innovation path mediated by market selection Machinery embodied know-how
<b>Competitive strategies and innovation coordination</b>	Focus on product design and development Organic Systems integration competences Management of multi-firm alliances in temporary projects	Focus on economies of scale/cost minimisation Mechanistic Volume production competences Focus on single firm (e.g. lean production, TQM, MRP 11)
<b>Industrial coordination and evolution</b>	Elaborate networks Project-based multi-firm alliances Temporary multi-firm alliances for innovation and production Long-term stability at integrator level	Large firm/supply chain structure Single firm as mass producer Alliances usually for R&D or asset exchange Dominant design signals industry shakeout
<b>Market characteristics</b>	Duopolistic structure Few large transactions Administered markets Institutionalised/politicised Heavily regulated/controlled Negotiated prices Partially contested	Many buyers and sellers Large numbers of transactions Regular market mechanisms Traded Minimal regulation Market prices Highly competitive

More recently Novak and Eppinger (2001) defined product complexity based on three main elements: (1) the number of product components to specify and produce, (2) the extent of interactions to manage between these components (parts coupling), and (3) the degree of product novelty. Whilst the first two elements are compatible with Simon's definition of complexity, including the level of innovation embedded in a product in the evaluation of its complexity constitutes a fundamental difference

between the two approaches and is probably driven by the changes to the industrial environment that took place in the last decades.

The differences between “simple” and complex products have an impact on the development and production processes and on the characteristics of the organisation, as described by Hobday (1998) and summarised in Table 2.2.

The product that was chosen for investigating knowledge arising from service and how it was reused was drilling equipment for the offshore oil rigs. It represented the common element across the selected case studies. Two companies, involved throughout the lifecycle of the drilling equipment, collaborated on the research. The main industrial collaboration is the supplier of the equipment already described in detail in Chapter 1. The second collaboration is a drilling contractor. This company owns the rigs where drilling equipment is installed and performs the drilling operations following instructions from the client oil company. The drilling contractor also defines the requirements that need to be taken into account by the supplier of the drilling equipment when designing and manufacturing the equipment.

Among the range of equipment and rigs characterising the business of the two companies, specific cases were selected in order to investigate the characteristics of knowledge from service and its transfer. Three case studies were carried out; the first two studies were in collaboration with the supplier of the equipment and were:

- A preliminary investigation (Preliminary Study) aiming to collect background information about the company and its knowledge management systems, and understand how these systems were accessed by service engineers and engineering designers;
- An analysis (Case Study I) of the knowledge generated during the service phase in relation to the knowledge needs of service engineers and engineering designers.

A further case study (Case Study II), that involved both the supplier of the equipment and the drilling contractor, investigated how knowledge from service was transferred and reused by the two companies.

The choice of focusing upon the drilling equipment for the oil industry arose from its unique characteristics:

- The design solutions are specific for each rig, or series of rigs, so re-design or adaptation of equipment and assembly is required in each project. Hence it is imperative to have the correct design the first time.
- The enormous costs of downtime of a rig (when the rig operations are interrupted) trigger the improvement of both the service support and the design of the equipment.
- The physical distance between the designers and the oil field where the equipment operates reduces the transfer of knowledge through informal networks of communication.
- Regulations and other requirements oblige to keep track of service interventions occurring throughout the lifecycle of the rigs.

#### 2.4.3 Maps of the case studies

Table 2.3 Case studies conducted during the descriptive phase and methods chosen.

	<b>Preliminary study</b>	<b>Case study I</b>	<b>Case study II</b>
<b>Focus</b>	Background knowledge and overview of knowledge management systems	Characteristics of knowledge from service and how this is perceived by service engineers and engineering designer	Mechanisms for transferring knowledge within the service phase and across phases of the product's lifecycle
<b>Company</b>	Supplier of drilling equipment	Supplier of drilling equipment	Supplier of drilling equipment and drilling contractor
<b>Methods for collecting data</b>	Document analysis, Survey	Semi-structured interviews	Semi-structured Interviews
<b>Methods for analysing data</b>	Quantitative	Quantitative and qualitative	Quantitative and qualitative

This section summarises the case studies conducted during the research project and illustrates which research methods have been chosen for each case study, as reported in Table 2.3.

The preliminary study aimed to gather background knowledge about the supplier of drilling equipment, the main industrial partner of the research project, and obtain an overview of the knowledge management systems that were adopted. The approach selected consisted of an initial quantitative analysis of available knowledge repositories, in order to obtain an overview of the type of information that was available and the criteria that could be used to retrieve it. This analysis of documentation was followed by a survey distributed among service engineers and engineering designers that focused upon how the two groups used the available documentation. Finally, a more detailed analysis of a specific type of documentation that the survey indicated as relevant for both service engineers and engineering designers, notifications of changes, was carried out.

This preliminary investigation provided insights on the type of information relevant for service engineers and engineering designers that constituted the foundation of the subsequent stages of the research project, when semi-structured interviews were conducted with service engineers and engineering designers in order to understand the characteristics of knowledge arising from the service phase of the drilling equipment and how this was transferred and reused by the different stakeholders.

#### **2.4.4 Research methods**

This section describes the research methods that were taken into consideration, and eventually adopted, whilst carrying out the case studies.

##### ***Data collection and analysis***

Two main approaches can be selected whilst conducting a research project: quantitative and qualitative approaches. Additionally a mix between the two could also be chosen in order to combine the advantages deriving from the two approaches; this solution represent a pragmatic strategy towards the research topic, that focuses on



obtaining the best possible understanding of the problem to tackle (Eisenhardt 1989, Creswell 2003). This approach, based upon the sequential use of both quantitative and qualitative methods was adopted in this research project.

A multiplicity of data collection methods were employed during this research project: namely document analysis, a survey and semi-structured interviews. The various methods were employed in order to obtain a complete picture of the knowledge arising from the service phase of complex equipment and how this was transferred within and across phases of the equipment's lifecycle.

The characteristics, advantages and limitations of each method are described below in general terms, whilst how each strategy has been applied to this research project is illustrated in Chapter 4.

#### Document analysis

Documents can be used for research purposes in two different ways: a researcher might analyse either documents created independently from the research study or specifically created for the particular research (Ahmed 2007).

The advantages of document analysis include that the data can be created without requiring the presence of the researcher; hence the researcher does not influence the practitioner while generating the data and the data can be collected over a longer period of time. Additionally, when the documents are not created for research purposes, the disturbance for the collaborating company is minimal. On the other hand, the limitations of document analysis derive from the influence of the format (i.e. structure) of the documents on the content, and difficulties for a researcher to deal with information that is sometimes hard to find, incomplete or inaccurate (Creswell 2003).

Document analysis was utilised in the preliminary case study, when available documents from the supplier of drilling equipment were analysed quantitatively with respect to the indexing criteria associated to the types of document stored in the company's repositories. Additionally, a type of document that was relevant for both service engineers and engineering designers, change notifications, was mapped

against the phase of the lifecycle in which they had been generated and the reason for change. This analysis provided a quantitative overview of the characteristics of changes.

The results from the document analysis were taken into consideration while formulating the questions of the semi-interviews.

### Interviews

Several forms of interview can be used for research purposes: open-ended, semi-structured (or focused) and structured (or survey). In open-ended interviews the respondent is asked to describe general facts or events or give his/her opinion on a topic. In this type of interview the respondent tends to become an informant as he/she describes events beyond the knowledge of the interviewer. In semi-structured interviews the interviewer follows a predetermined set of questions. A third type of interview is survey, where only specific questions are asked and the range of answers is predetermined (Yin 1994).

Limitations of collecting empirical data through interviews include the fact that information is filtered through the eyes of the respondent; data might be biased by the behaviour of the interviewer or the way the questions are posed, and answers reflect differences between the perceptive and articulating skills of the different respondents (Creswell 2003). A correct formulation of the questions is important for the validity of the investigation; particularly the questions should be posed in a way that limits the bias related to the interviewer's expectations and beliefs. In addition, reductive, common connotation and translation biases can be avoided by acquiring an extensive knowledge of the topic before conducting the interviews (Wood, Ford 1993). This facilitates the use of a shared lexicon and reduces the respondent's tendency to simplify concepts to make them more comprehensible.

Interviews are useful to capture explicit knowledge; however they do not allow capturing the implicit knowledge of the respondent. Also, they are retrospective, hence rely on interviewees memories and view of events (Ahmed 2007).

### Other approaches to data collection

Other approaches to data collection commonly used in research are observation and protocol analysis. However, neither of these approaches has been adopted during the research project as they were not considered suitable for the specific cases. An initial dialogue with the main collaborating company indicated barriers for the application of approaches that count on the researcher being present when the event of interest occurs.

Specifically barriers for the application of these approaches included:

- Logistics. The visits to the company had to be planned in advance as the researcher and the collaborating company were based in two different countries.
- The long timeframe for reusing knowledge from service and the difficulties in predicting when and how this knowledge is reused posed a barrier to the advance planning of observations.
- Urgency in solving a service case due to the enormous costs of a rig's downtime, and impossibility in foreseeing job tasks impeded protocol analysis.

Additionally, most of the knowledge that was expected to be reused was related to specific service cases, hence the researcher would not have been able to follow the rationale behind reusing knowledge without asking the participants for explanations. Detailed knowledge of the physical product, its development over time and the organisational structure (e.g. people, roles, departments, responsibilities) would have been necessary to obtain a full understanding of the event observed.

## **2.5 Prescriptive study**

According to the Design Research Methodology (Blessing, Chakrabarti 2009), the outcome of the descriptive study should provide the information that is necessary to generate a scenario of the desired situation. Assumptions, and possibly experience, can be used to develop the future scenario and the method leading to its generation.

The methodology to be followed when developing a prescriptive study is not widely accepted across research fields, as is also the case for the descriptive studies.

In this research project, the methodology used to elaborate the findings from the descriptive study in order to determine the ideal situation was based upon a constant verification of the assumptions made against literature. Specifically, the findings from the descriptive study on service knowledge and its transfer have been applied to the framework for knowledge reuse proposed by Kamara et al. (2002). Kamara's framework has been used to develop a knowledge management model aiming to facilitate the reuse of knowledge from service. This model will be described in Chapter 5.

## **2.6 Descriptive study II**

The knowledge management model proposed in the prescriptive study could not be implemented by the collaborating company within the time frame of the PhD project. Hence, an alternative way of testing its validity has been chosen and will be described in detail in Chapter 6.

The internal validity of the model was tested through a workshop organised at the supplier of drilling equipment that involved both service engineers and engineering designers; whilst the external validity of the model was evaluated through a comparative study between the oil and aerospace industry. This approach of testing the findings from a research study against a different context is in accordance with Eisenhardt's approach on building theories from cases (Eisenhardt 1989), which stresses the importance of trying to generalise research findings to make them applicable to different domains.

The model was evaluated based upon the five level evaluation approach proposed by Ahmed (2000), that is an extension of Kirkpatrick's four levels of training evaluation (Kirkpatrick 2009). According to Ahmed's approach, the results of a research project could be evaluated in terms of:

- *Validation*. The results are validated by testing their applicability to other contexts and their completeness against other empirical studies or literature.
- *Reaction*. Reaction evaluation is how participants felt about a training or learning experience.
- *Learning*. Learning evaluation is the measurement of the increase in knowledge, before and after the participants are introduced to the results, e.g. the proposed model.
- *Behaviour*: Behaviour evaluation is the extent of applied learning back on the job, e.g. how the model is implemented in practice.
- *Results*: Results evaluation is the effect of the strategy on the business or environment.

Both internal and external validity of the model were tested for reaction and validation.

### **Case selection**

The auxiliary case study was selected from the aerospace industry. This choice of industry was motivated by the balance between similarities and differences between aerospace and oil industries.

On the one hand, the aerospace industry, like the oil industry, deals with complex products, (see definition in Section 2.4). Additionally both industries do not admit failure during operation and need to keep track of issues and requests for changes arising during all the phases of the lifecycle due to international regulations and strict client requirements.

On the other hand the two industries are characterised by different development and production processes. Airlines, and their components such as the aeroengine, are examples of a variant design domain, with new designs that often reuse modules from past variants. On the contrary, the drilling equipment developed for offshore oil rigs is characterised by different combinations of customised equipment; hence, the final configuration of the drilling system is unique for each rig. Due to the one-off nature of

the drilling equipment, the testing phase is limited and takes place after the equipment has been built.

The model proposed to improve the reuse of service knowledge based on the findings from the oil industry was compared to the characteristics of the aerospace industry with regard to the reuse of service knowledge within the service phase. The long development time that characterises the development of new products in the aerospace industry did not allow for investigating the reuse of service knowledge during the design phase. The comparison aimed to verify whether the proposed model was suitable to address issues that were of relevance beyond the oil industry.

### **Data collection and analysis**

The information necessary to compare aerospace and oil industries with regard to service knowledge and the in-service support provided was gathered through a participatory research approach. Empirical evidence, in the form of interviews, observations and the analysis of the company's procedures, was provided by Yifan Xie, a PhD researcher from the University of Bath who works on the development of tools to improve knowledge management practices in collaboration with the aerospace company.

The information collected was used to compare the characteristics of the aerospace industry to those of the oil industry. Hence the model for reusing information from service that was developed through the prescriptive study was analysed with respect to its ability of answering the needs of the aerospace industry.

## **2.7 Summary**

This chapter has described the methodology adopted for conducting the research project presented in this thesis. First the concept of a research paradigm has been introduced; then the frameworks that represented the foundation of the project, specifically the concept of knowledge economy and the methodology for conducting research in the engineering design field, have been illustrated. Finally the stages that represented the subsequent phases of this project, in agreement with the Design

Research Methodology, have been defined and the methods adopted in each stage described.

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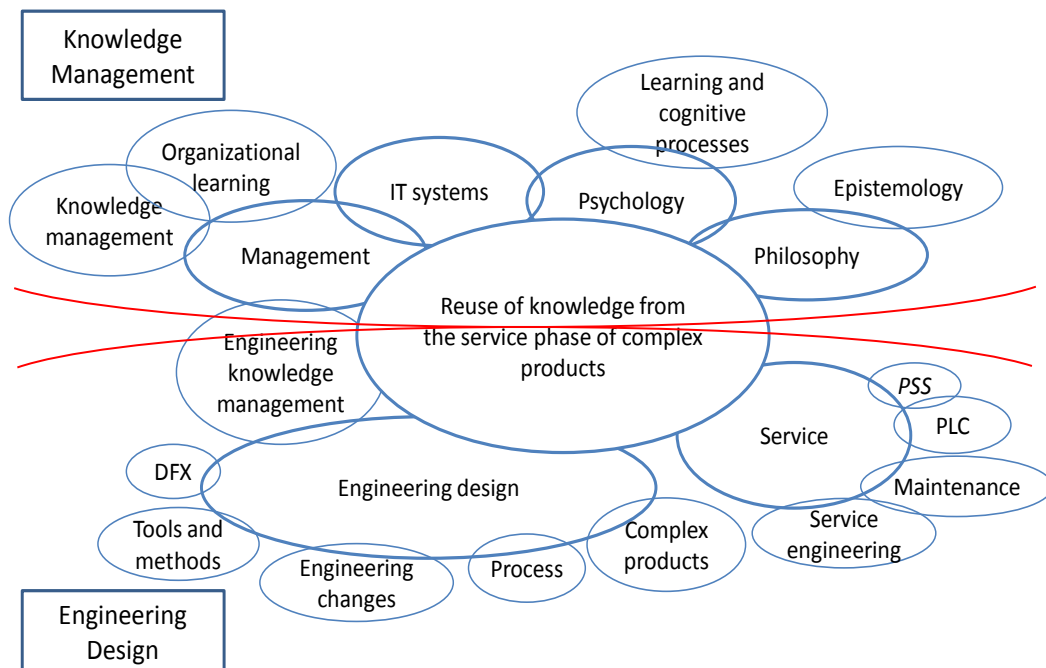


### 3. Literature survey

#### 3.1 Introduction

This chapter provides an overview of the concepts and frameworks that represented the foundation of the PhD project. The research spans across two distinguished areas. On the one hand, the investigation of how to “reuse knowledge” involved research domains such as philosophy and psychology, knowledge management and information technology. On the other hand, the investigation of “the service phase of complex products” related the research project to the engineering domain, e.g. engineering design and service design. These two areas and the main research topics within these areas are illustrated in Figure 3.1.

Figure 3.1 Theoretical framework of the research project. The upper part shows research areas investigating the reuse of knowledge, while the lower part indicates the areas studying a product’s lifecycle.



The relatively new research domain of engineering knowledge management, which was the domain where the researcher operated, aims to build a bridge between the two areas described above and apply theories on knowledge reuse to the engineering

domain. This literature survey first presents frameworks related to knowledge and how it is transferred, then provides an overview of the state-of-the-art research on knowledge management, investigating the relation between reusing knowledge and obtaining competitive advantage. Then the attention is moved towards the engineering design domain, introducing literature related to product lifecycle, development process and service phase. Consequently, the results of approaching knowledge management from an engineering perspective are presented through an overview of literature on engineering knowledge management and the main approaches towards knowledge management adopted in industry are illustrated.

Finally, the results from the literature review are discussed in relation to the research questions that this thesis aims to answer.

### **3.2 Knowledge definition**

Knowledge definition and classification is a topic of common interest to various disciplines, with entire areas of philosophy specifically dedicated to debating this topic.

A widely accepted definition of knowledge is Plato's definition of knowledge as "justified true belief": knowledge emerges from the reasoning about perceptive experiences (true beliefs), which are supported by the enumeration of the factors that make the beliefs true.

Various disciplines have tried to describe what knowledge is and situate it in relation to other forms of cognition, such as information and data. One such example is the definition of the DIKW (Data, Information, Knowledge and Wisdom) pyramid, shown in Figure 3.2, that represents the different entities in a hierarchy from the lower level, represented by data, to the higher level, embodied in wisdom (Ackoff 1989, Rowley 2007).

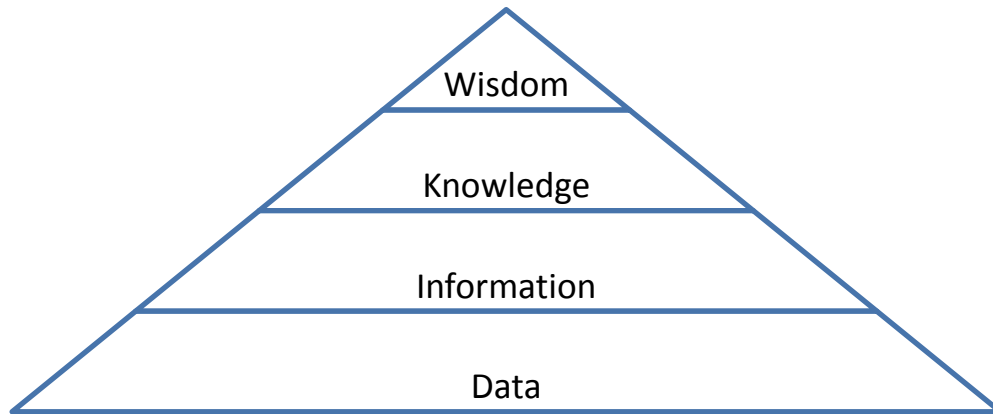


Figure 3.2 DIKW hierarchy (Ackoff 1989, Rowley 2007).

Data is a set of discrete, objective facts. Information is processed data, endowed with relevance and purpose. Data is transformed into information via e.g. contextualization and categorization. Knowledge is information possessed in the mind of individuals: it is personalised information related to facts, procedures, concepts, interpretations, ideas, observations, and judgments (Alavi, Leidner 2001). Finally wisdom comes from the ability to synthesise knowledge from different sources in order to make informed judgments about various ideas and propositions.

In relation to the DIKM hierarchy, most of the research from the engineering field has addressed the topic of knowledge management at the data and information levels, developing methods and tools to support its capture, structure and retrieval, with the aim of providing engineers with relevant information during their decision making process. In contrast, research in psychology has focused on the higher levels of the pyramid by investigating human cognition and learning and defining the phases that characterise skill acquisition. Anderson (1982) described this process as composing of three stages: 1) a declarative stage, when the learner obtains information about the skill; 2) a compilation stage, when the information is interpreted and converted into a procedural form and; 3) a procedural stage, when the use or the acquired skill is applied more and more appropriately. Hence, Anderson's model suggests the steps required to climb the DIKW pyramid and progress from information towards wisdom through an interiorization process.

The distinction between data, information, knowledge and wisdom has limited practical applications, as the concepts are more of a continuum, and are difficult to separate in practice due to the context of their use (Ahmed 2000). In this thesis a more pragmatic approach towards knowledge has been adopted, as proposed by VonKrogh et al. (2001). They introduced the concept of knowledge domain, consisting of a set of relevant data, information, articulated and tacit knowledge in relation to a particular subject. Hence the term “knowledge”, as used in this thesis, includes both explicit and tacit elements (see Section 3.3), while “information” is used interchangeably with codified knowledge, e.g. to indicate documentation.

### **3.3 Knowledge classifications**

Knowledge can be approached from a number of different perspectives, from considering it as an object, e.g. which can be stored or used, to seeing it as a state of mind, hence focusing on the learning process. The way knowledge is perceived directly influences the approaches adopted to manage it and the characteristics of the knowledge management strategy that need to be implemented in order to achieve the desired results. The most common knowledge perspectives are summarised in Table 3.1 (Alavi, Leidner 2001). Each perspective has led to the development of frameworks aiming to classify knowledge in relation to the characteristics that are relevant for the specific approach. Various frameworks have been proposed to classify knowledge. Those particularly relevant for this research project are:

- Know-what/ know-why/ know-how (Zack 1999);
- Tacit/ implicit/ explicit knowledge (Polanyi 1962);
- Static/dynamic knowledge (Nonaka 1994).

These classifications are described in detail in the following sub-sections.

Table 3.1 Knowledge perspectives and their implications, according to Alavi (Alavi, Leidner 2001).

<b>Perspective</b>	<b>Description</b>	<b>Implications for knowledge management (KM)</b>	<b>Implications for knowledge management systems (KMS)</b>
<b>Knowledge vis-à-vis data and information</b>	Data is facts, row numbers, information is processed/interpreted data, knowledge is personalised information.	KM focuses on exposing individuals to potentially useful information and facilitating assimilation of information.	KMS will not appear radically different from existing IS, but will be extended towards helping in user assimilation of information.
<b>State of mind</b>	Knowledge is the state of knowing and understanding.	KM involves enhancing individual's learning and understanding through provision of information.	Role of IT is to provide access to sources of knowledge rather than knowledge itself.
<b>Object</b>	Knowledge is an object to be stored and manipulated.	Key KM issue is building and managing knowledge stocks.	Role of IT involves gathering, storing and transferring knowledge.
<b>Process</b>	Knowledge is a process of applying expertise.	KM focus is on knowledge flows and the process of creation, sharing and distributing knowledge.	Role of IT is to provide link among sources of knowledge to create wider breadth and depth of knowledge flows.
<b>Access to information</b>	Knowledge is a condition of access to information.	KM focus is organised access to and retrieval of content.	Role of IT is to provide effective search and retrieval mechanisms for locating relevant information.
<b>Capability</b>	Knowledge is the potential to influence action.	KM is about building core competences and understanding strategic know-how.	Role of IT is to enhance intellectual capital by supporting development of individual and organisational competences.

### ***Classification by know-what/know-how/know-why***

Knowledge can be categorised according to the object it refers to, as (Zack 1999):

- Declarative knowledge, or know-what: knowledge describing something;
- Procedural knowledge, or know-how: knowledge describing how something occurs or is performed;
- Causal knowledge, or know-why: knowledge describing why something occurs.

In addition to these types of knowledge a fourth, supporting category, the “know of”, is related to the awareness of the existence of the knowledge and completes this categorisation. In an organisational context, the “know of” ensures that the members of an organisation are aware of the availability of knowledge and are able to retrieve and reuse it.

Declarative, procedural and causal knowledge, together with the “know of”, are referred in this thesis as knowledge *types*, in accordance with Zack (1999). This categorisation of knowledge is useful for knowledge management as the *type* of knowledge that is expected to be managed influences the characteristics of the knowledge management system adopted for handling it.

### ***Classification by explicitness***

A second classification, widely used across domains, takes into consideration the level of explicitness of knowledge and distinguishes between: tacit, implicit and explicit knowledge (Polanyi 1962).

Explicit knowledge can be articulated and stored in external repositories in the form of information. Implicit knowledge cannot be articulated by the person possessing it; however, it is possible to articulate it and store it externally after it has been extracted through knowledge elicitation methods. Tacit knowledge is knowledge that cannot be articulated (Wallace, Ahmed et al. 2005).

A related categorisation makes a distinction between personal and codified knowledge, and is directly applicable to the way knowledge can be transferred (McMahon et al. 2004). Personal knowledge is embedded within the person

possessing it and can be explicit, implicit or tacit. On the other hand codified knowledge is knowledge captured in documentation; it can be paired to information and only refers to explicit knowledge.

### ***Classification by static/dynamic***

Another classification of knowledge distinguishes between static and dynamic knowledge. Static knowledge is generated and used in a static environment through a sequence of hierarchical information processing that follows a problem solving approach. On the contrary, dynamic knowledge needs to be related to the context when it was generated and continuously revised taking into account the changes in the environment (Nonaka 1994).

### **3.4 Knowledge acquisition and transfer**

The distinction between tacit and explicit knowledge is fundamental for analysing the phenomenon of knowledge creation and transfer, as the creation of new knowledge is based on a continuous process of interactions between explicit and tacit knowledge (Nonaka 1991). The combination of the two categories occurs through four conversion patterns, described by the SECI (Socialisation, Externalisation, Combination, Internalisation) model. According to this model the patterns of knowledge conversion are (see Figure 3.3):

- From tacit to tacit: through socialisation;
- From tacit to explicit: through externalisation;
- From explicit to explicit: through combination;
- From explicit to tacit: through internalisation (representing the traditional notion of learning).

		To	
		Tacit knowledge	Explicit knowledge
From	Tacit knowledge	Socialisation	Externalisation
	Explicit knowledge	Internalisation	Combination

Figure 3.3 SECI model (Nonaka 1994)

Three of the four types of knowledge conversion - socialisation, combination, and internalisation - are described in organisational theory. Socialisation is connected with theories of organizational culture, combination is rooted in information processing and internalisation is associated with organizational learning. By contrast, the concept of externalisation has been covered by literature on knowledge creation from the individual point of view, but has not been extensively investigated from the organisational point of view.

Various frameworks that have described the phenomenon of knowledge creation and transfer in an organisational context are based upon Nonaka's analysis of knowledge creation. Three of those frameworks describing knowledge transfer are discussed in the following section. The first framework analyses knowledge transfer from an organisational point of view, the second defines the phases of the knowledge transfer process, and the third focuses on knowledge transfer in relation to the actors involved in the process.

#### 3.4.1 Frameworks for knowledge transfer

##### ***Knowledge transfer in organisations***

Argote and Ingram proposed a framework based upon empirical evidence to describe the phenomenon of knowledge transfer in organisations (Argote and Ingram 2000). They identified three basic elements for transferring knowledge at the organisational level: tools, tasks and members. The elements themselves and the networks formed by



their combination are identified as reservoirs of the organisation's knowledge. Tools represent the technological elements within the organisation; tasks represent the goal and purpose, while members are the individuals who form the organisation resources. The framework suggests that knowledge transfer can occur through two distinct mechanisms:

- Moving a knowledge reservoir into a different context: e.g. adopting a software tool, which is already in use in one department, in other parts of the organisations.
- Modifying a reservoir at the recipient side: e.g. enhancing the knowledge of employees through a training programme.

To have a positive impact on organisational performance the networks formed by pairs of the three basic elements of the reservoirs must be compatible with other networks within the organisation. From a management perspective the aim of knowledge transfer is to increase the competitiveness of a company, hence the ideal objective of the process is to enhance the company's internal knowledge in a way that is difficult to replicate for other companies. Argote and Ingram identify the network member-to-member as the reservoir that best fulfils this need, as the interactions between members of an organisation can be transferred within the organisation thanks to the ability of individuals to adapt to different environments, however it is not likely to be adapted to other organisations as it is influenced by the characteristics, routines and specific culture of the company.

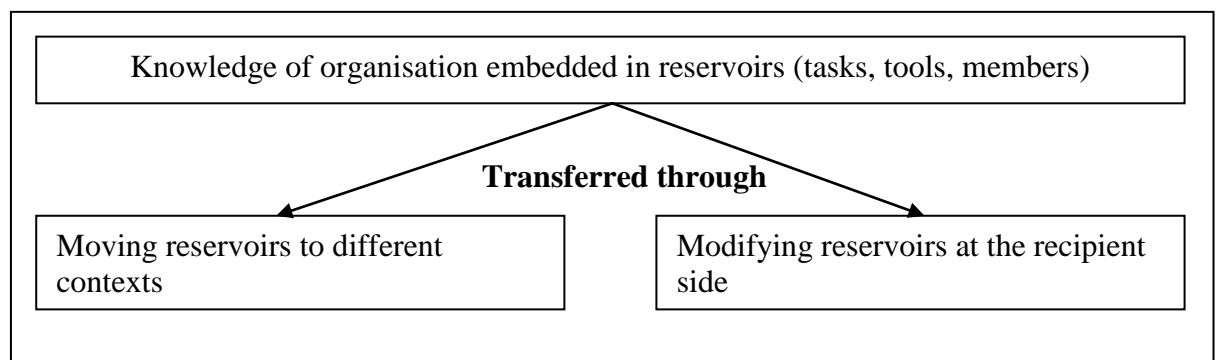


Figure 3.4 Argote *et al.*'s framework on knowledge transfer (Argote and Ingram 2000).

The framework described overleaf and summarised in Figure 3.4 provides a general description of possible knowledge transfer mechanisms, however it does not describe the different stages that constitute the knowledge transfer process or the types of knowledge that are relevant to be transferred in order to increase the competitiveness of the company.

### ***Phases of knowledge transfer***

Other authors have proposed frameworks that focused on the description of how knowledge transfer occurs. Specifically, Gilbert and Cordey-Hayes identified the subsequent phases of knowledge transfer, namely acquisition, communication, application and assimilation (Gilbert, Cordey-Hayes 1996). They state that true learning occurs only in the last stage where the process results in the development of core organisational routines and practices, although the transfer of knowledge is already effective in the application phase (see Figure 3.5). This framework mirrors, at the organisational level, the framework describing the cognitive processes of the individual that have been proposed by Anderson (Anderson 1982) and summarised in Section 3.2.

The vision of knowledge transfer suggested by Gilbert and Cordey-Hayes is complementary to Argote's framework when transfer occurs through modifying knowledge at the receiver's side, but excludes transfer through moving knowledge reservoirs to other contexts.

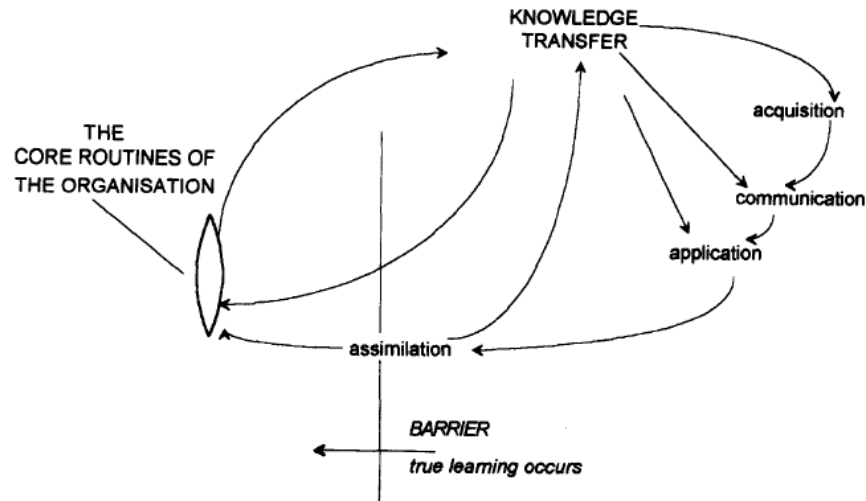


Figure 3.5 Framework for knowledge transfer proposed by Gilbert and Cordey-Hayes (1996).

### ***Sender - Receiver framework for knowledge transfer***

When focusing on communication, knowledge transfer may be seen as either symmetric or asymmetric. Figure 3.6 illustrates the two forms of knowledge transfer in relation to the completeness of the information exchanged.

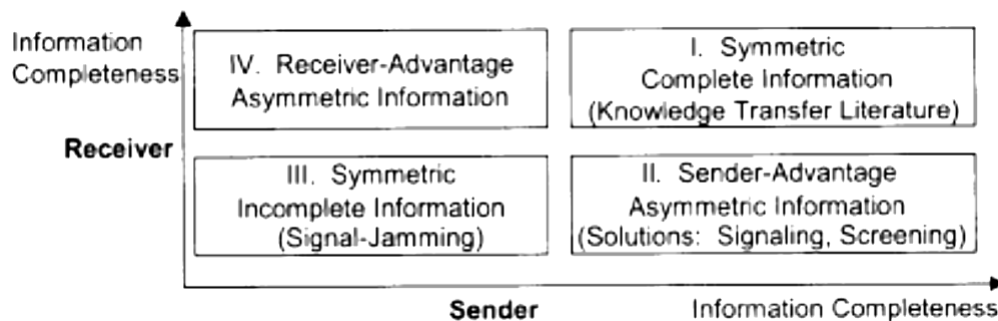


Figure 3.6 Information value in knowledge transfer (Lihui Lin, Xianjun Geng et al. 2005)

Today, the prevalence of distributed forms of organisations and frequent inter organisational relationships have led to a prevalence of asymmetric transfer. This type of transfer can be analysed through a sender-receiver framework that investigates knowledge transfer with respect to motivational issues, trust between the parties involved and completeness of the shared information. The degree of shared understanding between the sender and receiver influences the value of information as it affects the ability of the receiver to take advantage of it (Lihui Lin, Xianjun Geng et al. 2005).

Asymmetric transfer of knowledge that involves parties from different disciplines or organisational contexts facilitates innovation as dissimilarity is a condition for learning and bringing together different perspectives supports the exploration of new solutions (March 1991). However, this involves more complex mechanisms than the transfer of knowledge within a homogeneous group. According to Carlile's framework for managing knowledge across boundaries (Carlile 2004), when a pragmatic boundary is present, that is when the parties have different interests, the simple transfer of available knowledge is not enough; it has to be translated according to the receiver's needs in order to be successfully shared.

Table 3.2 Strategy to support knowledge transfer (Zack 1999).

		Symmetric transfer	Asymmetric transfer
<b>Context</b>	<i>Shared understanding (codification)</i>	Repositories used to integrate and build on collective knowledge (integrated knowledge base)	Repositories gather stable knowledge accepted by the receiver (electronic publishing)
	<i>Limited understanding (personalisation)</i>	Communication between people performing common practices (forums)	Knowledge transfer between expert and novice (distributed learning)

Possible strategies to support knowledge transfer in relation to the level of mutual understanding between sender and receiver and the involvement of the receiver in knowledge creation are summarised in Table 3.2. When the two parties share an understanding of a topic, the most suitable strategies are based on codification, whereas when the receiver only has a limited understanding of the topic personalisation strategies are usually more effective (Zack 1999).

### 3.5 Knowledge management

*A firm's competitive advantage depends more than anything on its knowledge. Or, to be slightly more specific, on what it knows – how it uses what it knows – and how fast it can know something new (Prusak 1997).*

From the 1990s, the diffusion of a knowledge-based view of the firm suggested that knowledge is the most strategically significant resource of a firm, as what firms do better than individuals is the sharing and transfer of the knowledge between members of the organisation (Kogut and Zander 1992). According to the knowledge-based theory of the firm, knowledge-based resources are usually difficult to imitate and socially complex; hence, the knowledge and capabilities available within a firm are the major determinants to achieve competitive advantage and superior performance.

Grounded on these premises, research on knowledge management has focused upon the optimisation of the exploitation of knowledge in the context of organisations, to achieve enhanced performance, increased value, competitive advantage and return on investment. Managing knowledge involves taking into consideration both individual and collective knowledge and developing strategies through the analysis of the context (the organisation where knowledge needs to be exploited) and the identification of the content (the knowledge that needs to be reused) (Kamara et al. 2002).

### **3.5.1 Knowledge management schools**

Knowledge management can be approached from different perspectives, depending on whether the attention is more focused upon personal knowledge, codified knowledge, or the improvement of a firm's performances that can be achieved through knowledge management. Earl identified three distinguished schools of knowledge management (Earl 2001):

Technocratic: that sees knowledge as information and is focused upon the development of tools facilitating knowledge management.

Economic: that sees knowledge management in relation to the financial advantages that a firm can achieve and perceives knowledge as a financial asset.

Behavioural: that considers knowledge in relation to the organisational structure.

The characteristics of each of the three schools are illustrated in Table 3.3.

Table 3.3 Knowledge management schools and their attributes (Earl 2001).

	<i>Technocratic</i>		<i>Economic</i>		<i>Behavioural</i>		
	<b>Systems</b>	<b>Cartographic</b>	<b>Engineering</b>	<b>Commercial</b>	<b>Organisational</b>	<b>Spatial</b>	<b>Strategic</b>
<b>Focus</b>	Technology	Maps	Processes	Income	Networks	Space	Mindset
<b>Aim</b>	Knowledge bases	Knowledge directories	Knowledge flows	Knowledge assets	Knowledge Pooling	Knowledge exchange	Knowledge capabilities
<b>Unit</b>	Domain	Enterprise	Activity	Know-how	Communities	Place	Business
<b>Example</b>	Xerox	Bain & Co	HP	IBM	Shell	Skandia	Unilever
<b>Critical success factor</b>	Content validation Incentives to provide content	Culture/ incentive to share knowledge Networks to connect people	Knowledge learning and unrestricted distribution	Specialist teams Institutionalised process	Sociable culture Knowledge intermediaries	Design for purpose encouragement	Rhetoric artefacts
<b>Principal IT contribution</b>	Knowledge-based systems	Profiles and directories on Internets	Shared databases	Intellectual asset register and processing system	Groupware and intranets	Access and representational tools	Eclectic
<b>Philosophy</b>	Codification	Connectivity	Capability	Commercialisation	Collaboration	Contactivity	Consciousness

Most of the research on knowledge management conducted in the engineering field is aligned with the technocratic approach. It aims to develop knowledge-based engineering systems (Chapman and Pinfold 1999) and proposes new software tools to support the management of information (Bracewell et al. 2004). However, a new awareness that the development and implementation of IT solutions is not always the best strategy to support knowledge management has recently characterised the engineering domain as well. Researchers in knowledge management from engineering have started investigating how to develop knowledge management strategies that take into consideration factors that go beyond the technical challenges related to the development of IT tools, such as the type of information that engineering design would like to have access to (Jagtap et al. 2007).

### 3.5.2 Knowledge lifecycle

Knowledge lifecycle covers the series of stages from creating new knowledge to using and eventually modifying it. Several models have been proposed in literature to describe knowledge cycles. Foo et al. analysed the characteristics of these models and

synthesised the common fundamental stages, which need to be taken into consideration while developing a knowledge management system, as each stage has specific needs in relation to how knowledge is managed and supported (Foo et al. 2007). These stages are:

- Knowledge creation and capture: knowledge workers create new knowledge that is captured through organisational procedures.
- Knowledge organisation and storage: firm's infrastructures (e.g. repositories) provide the support required to organise knowledge in a way that allows creating value (in terms of re-exploitable knowledge).
- Knowledge search and transfer: this phase is focused upon the competitive advantage that can be obtained from reusing the available knowledge assets when new opportunities arise.

The model proposed by Sainter et al. is one of the various knowledge lifecycle models available from literature (Sainter et al. 2000). It defines the phases that constitute the ideal knowledge lifecycle and has been proposed as support for assessing the knowledge management processes adopted in a firm, since it helps identify the processes that would benefit from the implementation of a knowledge management tool.

According to Sainter et al.'s model, the phases of the knowledge lifecycle are (see Figure 3.7):

- Knowledge identification: knowledge relevant for a specific case is identified based on previous experience.
- Knowledge acquisition: knowledge is acquired from various sources.
- Knowledge selection: knowledge is evaluated and selected.
- Knowledge structuring: knowledge is structured taking into consideration the way it is supposed to be accessed for future retrieval.
- Knowledge storage: knowledge is stored in repositories.

- Knowledge transfer and use: knowledge is transferred and used in a different context.

The analysis of a specific industrial case against the model is expected to help define the characteristics of each of the phases and identify which phase needs to be improved before starting developing any kind of tool or application for knowledge management.

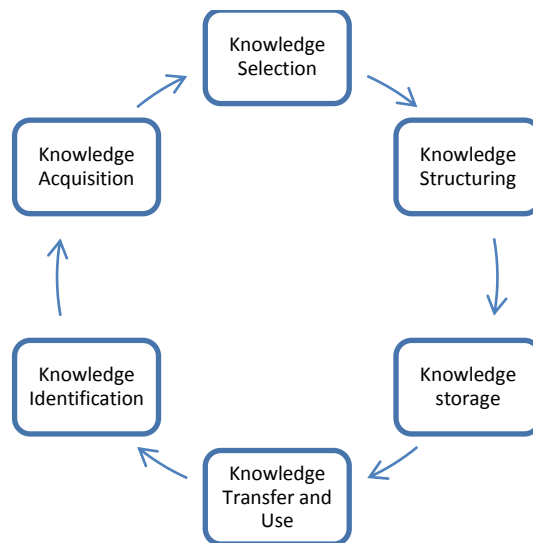


Figure 3.7 Phases of the knowledge lifecycle (Sainter, Oldham et al. 2000).

Knowledge lifecycle can also be investigated in relation to the number of people able to obtain value from the reuse of knowledge (Birkinshaw, Sheehan 2002). In this case, the lifecycle is divided into four stages, as illustrated in Figure 3.8:

- Creation: new knowledge is generated in an environment that couples creativity with rigour and structure.
- Mobilisation: knowledge is refined and the idea is developed in order to create value.
- Diffusion: the company starts proposing the new idea or concept within the company and to external stakeholders like clients, customers and media.
- Commoditisation: knowledge is already well known, however it still needs to be managed.



Birkinshaw and Sheehan stated that companies must use different strategies to realise maximum value in each of the four phases of knowledge development.

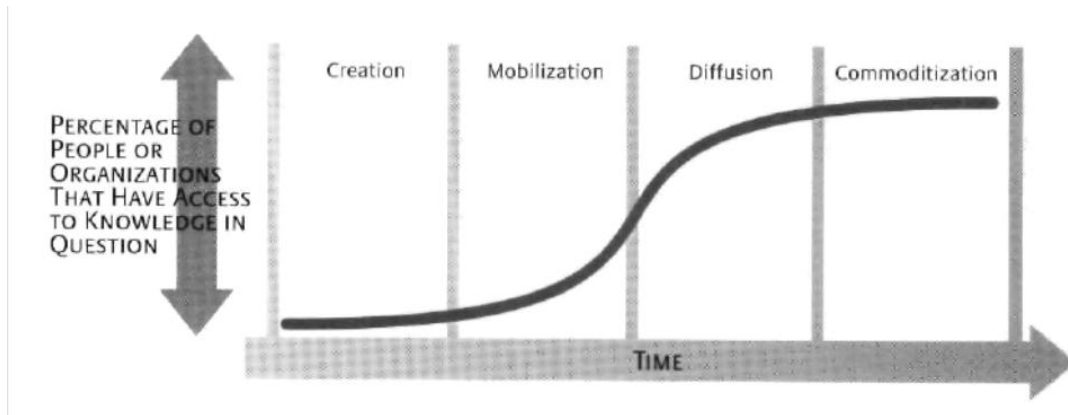


Figure 3.8 Knowledge progresses through four stages, as it develops over time and becomes accessible to more and more people, initially within and then outside the organisation (Birkinshaw, Sheehan 2002).

### 3.6 Engineering design domain

The project presented in this thesis investigates how to effectively reuse knowledge that is generated during the service phase of a product's lifecycle. This section provides an overview of the research on engineering design that is relevant for the project. The areas covered are: product lifecycle, engineering change management and engineering knowledge management.

#### 3.6.1 Product lifecycle

The development of a new product is triggered by a market need or a new idea. It starts with product planning and ends when the product's useful life is over, with recycling or disposal (Pahl, Beitz 1996).

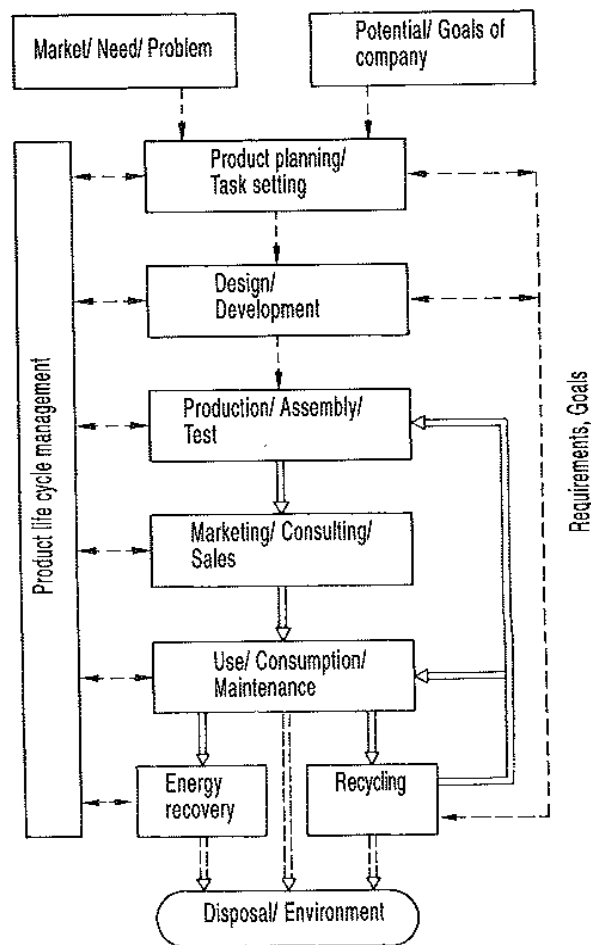


Figure 3.9 Scheme of a product's lifecycle (Pahl, Beitz 1996)

The generic succession of phases that characterise a product's lifecycle is represented in Figure 3.9. However, in industrial practice the lifecycle of a product differs from the standard scheme as it is influenced by the characteristics of the specific case (Pahl, Beitz 1996), for instance:

- Origin of the task: the motivation for creating a new product influences its lifecycle; e.g. a product's lifecycle does not include traditional marketing and sales when a customised order is received directly from the client.
- Organisation: the organisational structure of a firm influences how tasks are allocated across departments.
- Production volumes: the amount of prototyping and testing increases when going from one-off, to batch produced, to mass produced products.

- The degree of novelty: a product and its parts may be based on original design or adapted, reusing existing solutions.
- Complexity: the variety of domains and systems involved in the design of a product influences the processes to follow during its development and manufacturing.
- Branch: mechanical, electrical, software products are characterised by specific requirements (precision, efficiency, reliability).
- Goals: the purpose of a project (improve performances, reduce costs) influences the requirements of each phase of the lifecycle.

The next sections describe in more detail the development and service phases of the product's lifecycle, as these are particularly relevant for this thesis.

### 3.6.2 Product development process

The development process covers the first part of a product's lifecycle, from the conceptual phase to ramp up; it represents the sequence of activities undertaken by engineering designers in order to define a product and make it ready for production. Each step of the process can be seen as a problem solving activity where engineering designers clarify a sub-task by the identification of the relevant knowledge and then process that knowledge into a state that defines the selected sub-solution. The final product definition is an appropriate combination of all the selected sub-solutions (Ahmed 2000).

The main activities of a general development process are illustrated in Figure 3.10.a (Ulrich, Eppinger 2003). Figure 3.10.b and 3.10.c represent two variants, which are used when developing specific products. Figure 3.10.b represents the development process adopted for software and other products where the cost of the production tooling has a limited impact on the total cost of a product; in this case the final product definition is obtained through iterative design-build-test loops. Figure 3.9.c represents a development process where the development of each system is carried

out in parallel and followed by an integration phase; this process is used when dealing with complex systems.

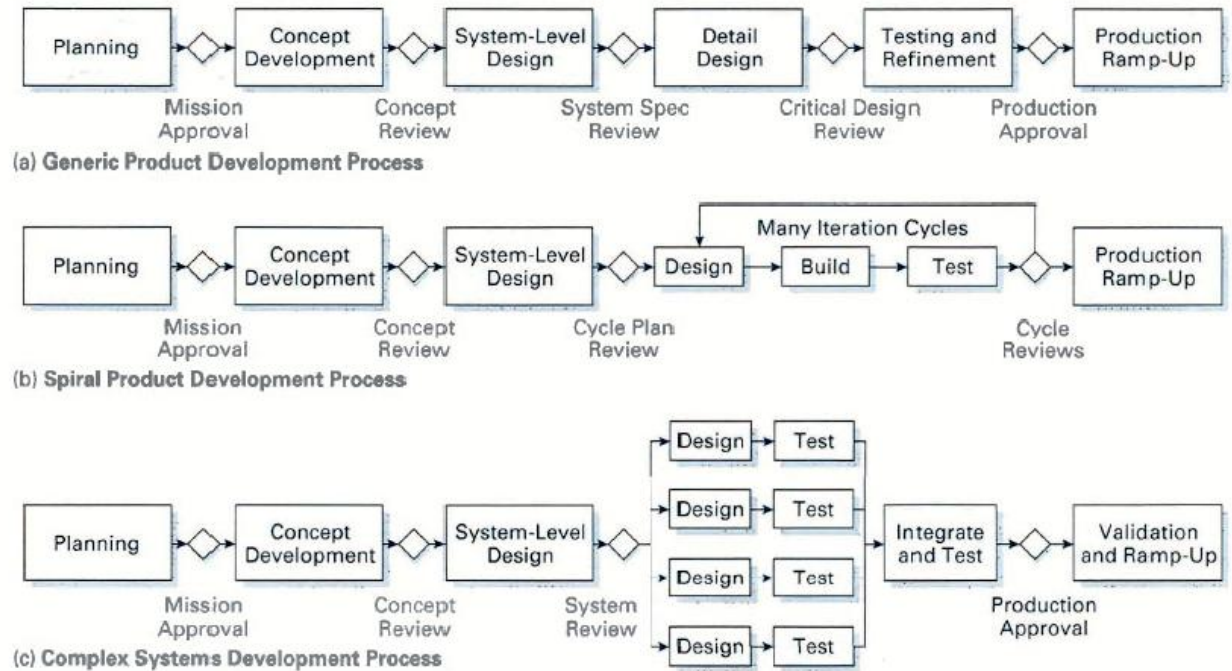


Figure 3.10 Product development processes for different types of products (Ulrich, Eppinger 2003).

### 3.6.3 Service phase

The word *service phase* is used in the thesis to indicate the part of the product's lifecycle when service engineers are involved. This phase includes the use, consumption and maintenance of the product in question and it is often referred to as operation phase (it is called *use/consumption/maintenance* in Figure 3.9).

In the last decade the service phase of a product's lifecycle has captured the attention of practitioners and researchers in the engineering design area. It has been widely acknowledged that the users determine the value of a product based on its performance and ability to answer the day-to-day operational requirements when in use (Sakao, Shimomura 2007). Additionally, manufacturing firms are interested in finding new business approaches, as differentiating mature products with respect to price, function and design is not always possible (Tan 2010).

These are the underlying premises that have motivated academics to research on Product-Service Systems and industry to move, from merely selling a product, to taking responsibility of a product's behaviour throughout its lifecycle (as in the case of the aerospace industry that current provide power-by-the-hour instead of selling the engines).

One consequence of the growing interest for the service phase is the need for companies to implement knowledge management systems covering the entire lifecycle of their products. Although current progresses in managing information include the use of metadata to facilitate the retrieval of documentation available in knowledge repositories, research is still needed in order to understand how to efficiently capture and retrieve information, especially for knowledge generated at the later phases of a product's lifecycle (Wallace 2005).

#### **3.6.4 Knowledge management in engineering**

In the engineering field the interest in knowledge management is motivated by the growing amount of technical knowledge that a company has to capture, structure and organise in order to facilitate its future reuse. For example, in the case of variant design, up to 70% of information is reused from previous solutions (Khadilkar and Stauffer 1996). Furthermore, current trends in engineering design include the consideration of issues related to the later phases of a product's lifecycle during the design process, resulting in the need to organise information from the lifecycle in a way accessible for engineering designers.

The current flexibility of the job market reduces the probability of an engineer to have a lengthy career within a single company. This limits the build up and reuse of personal expertise across projects and motivates companies to implement new approaches to facilitate the learning process and the reuse of past experience. Empirical studies have shown the difficulties for novices to formulate questions and define what they are looking for, hence highlighting the need to guide their access to knowledge (Ahmed et al. 2003). The solutions range from strategies focused on personalisation (McMahon et al. 2004) aiming to support the sharing of knowledge

within the organisation by building personal networks amongst employees (Wenger 2000) to codification strategies that try to solve issues connected with knowledge management through information and communication technologies (McMahon et al. 2004). Selecting the appropriate approach is influenced by the type of organisation and product.

A limited number of studies have been conducted in the engineering field to investigate the knowledge arising during the service of products and how this can be reused to support engineering designers during the design of similar products. Jagtap et al.'s research (Jagtap et al. 2007) investigated the service phase from a design perspective through a case study from the aerospace industry. They identified the main requirements for service knowledge for engineering designers as: maintenance and failure data, reliability, service instructions and lifecycle costs. Additionally, the research also identified the information engineering designers would like to access. Failure, operating and maintenance data, together with design information, lifecycle costs and life of component were identified as the main types of information to be included in a service information repository for the aerospace industry. The structure of service information was found to be critical for its reuse by engineering designers as quick retrieval of documentation available from different repositories is imperative in order to achieve a systematic reuse of information from service.

Wong et al.'s case study, also from the aerospace domain, resulted in a proposal for organising service knowledge and incorporating it into the design phase based upon service-oriented architecture. They proposed to integrate different knowledge repositories (Wong et al. 2007) through the definition of an ontology suitable for the aerospace industry. This ontology contains concepts ranging from engine deterioration mechanisms, engine models to airport locations.

A more general ontology, applicable to searching and indexing engineering knowledge, has been developed by Ahmed (Ahmed 2005) based upon four root concepts: design process, physical product, functions and issues, hence allowing multiple search criteria. Each of the root concepts constituting this ontology has

taxonomies and a suitable thesaurus defined. The taxonomies for product and the design process need to be generated according to the context of the specific industry. Reusing knowledge from service within the service phase of current and future products appears to be a more immediate way of taking advantage of experience from past cases, if compared to the transfer of service knowledge across lifecycle phases, as it does not involve crossing organizational boundaries (Carlile 2004). However, this is not systematically done in industry and it has only marginally been investigated in academic research. While research has investigated how to feed service information back to designers in order to improve the next generation of products, surprisingly little work has studied the specific expertise arising from servicing a product and how to transfer it within service to support service engineers while performing their work.

### **3.6.5 Engineering changes**

The review of literature on knowledge management stressed the importance of identifying the relevant knowledge before starting the development of a knowledge management strategy. In the case of engineering design, knowledge related to issues (e.g. operational failures) and the consequent changes to the product's design that is continuously generated throughout the lifecycle, is perceived as important by engineering designers (Jagtap et al. 2007). This makes this type of knowledge relevant for the research project presented in this thesis, as its transfer and reuse across the phases of the lifecycle and across products allows avoiding the repetition of issues already detected. A summary of literature on engineering changes is hereby presented. Engineering change (EC) is a modification to a component of a product, after the original design task has been completed. ECs have been categorised in several ways including: by the initiator of the change (Ahmed and Kanike 2007) or by the cause of the change (Jarratt 2004). A change can be initiated either internally or externally, depending upon whether the need for change arises from inside or outside the company. The definition of this categorisation varies according to the company's business model (Ahmed and Kanike 2007); however the understanding of the initiation of change is important since it influences the change management process.

Internal changes can be avoided, with an improved initial design, or at least implemented in the early phases of the product's development; whilst the impact of external change requests can be reduced only by designing more flexible products or components or through flexible specifications.

The management of engineering changes is generally formalised in a four step process: (1) changes are initiated by the submission of an engineering change request (ECR); (2) the ECR is evaluated and (3) engineering change orders (ECO) are distributed. (4) Finally ECO are recorded for future retrieval. This process of managing EC has captured the interest of researchers since the 1980's, initially being perceived as the process of merely correcting previous mistakes and with no effort made to understand how a product's changes could be turned into a competitive advantage. This view of EC characterised the majority of literature until the mid 1990s, as pointed out by Wright in his literature review of the topic (Wright 1997).

ECs were generally considered a problem rather than an opportunity and analysed exclusively from a manufacturing point of view. The issues of reducing engineering changes and limiting their impact have been approached in two different ways: (1) research focused upon developing computer based tools for the analysis of EC problems and (2) methods to reduce the impact of EC on manufacturing and inventory control. Wright stresses the need for further research from a marketing perspective to understand how to turn the EC process into a means for a company to stay effective within a competitive environment (Wright 1997).

Research on engineering change practice in industry has highlighted through various case studies that the time spent on managing changes required for EC processes is significant when compared to the time needed for product development (Soderberg 1989, Lincke 1995, McIntosh 1995, Blackburn 1992). The time required for implementing changes has a large impact on the cost of product development. Several studies have tried to quantify these costs and, despite differences from case to case, there is a general agreement among authors on the influence of EC on the total product development costs, i.e. in large development projects EC management



consumes one third to one half of engineering capacity (Soderberg 1989) and represents 20-50% of tool costs (Lincke 1995). According to McIntosh (1995), ECs could affect between 70-80% of the final product's cost. Despite these high costs, ECs do not significantly improve the product characteristics and the portion of time spent to enhance the product value is low (8.5% in airframe manufacturing) due to the long waiting time in responding to changes (Blackburn 1992).

The cost of addressing changes also increases with the product's development process, Carter and Baker (1992) state that a design change after full scale production may be ten times as expensive as an equivalent design change identified at the conceptual stage of design and increases by an approximate factor of 10 as each phase of the product's lifecycle is surpassed (Ahmed and Kanike 2007, Carter and Baker 1992, Terwiesch and Loch 1999). A case study from the automotive industry identified the main factors contributing to the long lead times, and the consequently high costs, for implementing changes as: 1) complex approval process, 2) snowball of changes, 3) scarce capacity and congestion, 4) setups and batching and 5) organisational issues. Principles proposed as a result of the study, to reduce the negative consequences of ECs, include (Terwiesch and Loch 1999):

- Avoiding unnecessary changes;
- Detecting ECs early;
- Speeding up the EC process.

These principles are still very broad, and further research is required to understand how these can be achieved. Huang et al. confirm Wright's analysis and, through a survey among UK manufacturing industries, have stated that industry generally ignores the capacity of changes to drive product improvement (Huang and Mak 1999). Furthermore, Huang identified the main barriers for an efficient change management as communication issues and the late discovery of problems with the consequent need for quick solutions. Lee et al. (2006) stressed the importance of the retrieval and reuse of past experience for the evaluation of ECRs and suggested that an important aspect for the improvement of the management of ECs regards storing,

not only the documentation related to the change approval, but also the rationale behind the decision-making process. Lee et al. also identified a general lack of a structured knowledge management practice when dealing with changes and proposed a model to support the management of engineering changes through the retrieval of past experience (Lee et al. 2006). This model compares changes through similarity criteria. However, a single similarity criterion is not adequate to retrieve past experience relevant for a new change case and a suitable ontology has been developed, as retrieval based on ontology is one of the most efficient ways to capture similarities between two engineering change cases. This is in agreement with the importance of developing suitable ontologies in order to facilitate information retrieval that has been highlighted by research on engineering knowledge management (see Section 3.6.4)

One of the most demanding tasks for effective management of changes is the forecast of the consequences of a change on other parts of the product, i.e. change propagation. Recent research shows that a change in a complex system can affect other parts of the system, even those that are not physically connected (Giffin et al. 2007, Keller et al. 2005). Each component can be classified as multiplier, absorber, carrier or constant, according to its characteristic of generating, absorbing, transmitting or being invariant to changes. Design efforts should be focused on multipliers in order to reduce subsequent changes to these components and to limit change propagation. Approaches that aim to avoid unforeseen change propagation, e.g. CPM (change prediction method), include the development of a tool that allows designers to visualise the consequences of a change before implementing it (Keller et al. 2005).

Giffin et al. (Giffin 2007) show that the number of change requests increases significantly during the integration and testing phases and it does not peak during the conceptual phase as assumed by previous research. A separate study highlights that around 75% of the changes are found in the manufacturing phase, the study followed an eight year period of an aeroengine, with two years of service (Ahmed and Kanike 2007).

This review of literature on EC has shown research on EC from various perspectives, and has discussed the main research approaches. Most of the reviewed studies have highlighted the need to change the industry's approach towards EC, and start thinking of EC as a means of improvement. However, lead time and costs connected with the change process have to be reduced, or industry will keep considering changes as a problem and not a way to improve a product.

### **3.7 Knowledge management in industry**

The majority of knowledge management practitioners see IT as the principal tool for managing knowledge, as it allows collecting, manipulating, and delivering an increasing amount of information, hence managing the organization's intangible assets more efficiently (Spender 2008). However, in traditional organisations knowledge flow is seen as a one-way flow of instruction rather than a two-way discourse between those with divergent views (Nonaka 1991), and knowledge generated in the later phases of a product lifecycle, e.g. by the users, is generally not reused systematically.

Several studies on knowledge management and organisational learning claim that firms with clear strategies in knowledge transfer are more successful than those without these (Zander and Kogut 1995) and propose frameworks to better analyse the phenomenon. In general, research studies have adopted a positive approach towards knowledge management, highlighting the importance for a company to be able to efficiently manage its internal knowledge in order to achieve competitive advantage, while a limited number of studies have described failures in managing knowledge and the related consequences (Storey and Barnett 2000). However, industrial practice often shows that development and implementation of a knowledge management strategy does not lead to the expected positive effects. For instance, according to Lucier from Booz-Allen & Hamilton (Lucier and Torsilieri 1997), 84% of knowledge management programmes fail to have a real impact. Robertson (Robertson 2003) identified recurrent issues with regards to knowledge management from the analysis of industrial practice, including:

- Inconsistent and unstructured approach to information management;
- Lack of knowledge sharing between related business units;
- Difficulties in determining and disseminating ‘best practices’;
- Over reliance on long-service members of staff as sources of knowledge;
- Cultural barriers between head office and regional staff.

Additionally, Robertson highlighted the problems related to the implementation of solutions directly taken from knowledge management programmes successfully adopted by other organisations, as these solutions may not lead to an equivalent result if they do not meet the actual organisational needs.

*“In practice, organisations are littered with well-meaning but poorly targeted knowledge management activities. In many cases, these failed because they simply didn’t address a clear, concrete and imperative problem within the organisation.”*

(Robertson 2003)

The lack of target is recognised as one of the critical factors for the success of a knowledge management strategy, as it is essential for the success of a strategy to identify the knowledge needs of an organisation and specifically address them.

The importance of developing a knowledge management strategy targeted to answer the needs of the organisation is confirmed by other research studies. For instance, Storey (Storey and Barnett 2000) has mentioned insufficiently defined business objectives and inadequate focus on a few main priorities as two of the most important barriers for the development of a successful knowledge management strategy.

Knowledge management strategies proposed in literature will be described in more detail in Chapter 5, where they will be used as a framework to develop a model describing how to reuse knowledge, which is addressed to the case studies investigated in this research project.

### 3.8 Implications for the research project

In this section, first the topics covered by the literature survey are summarised and related to this research project; then the implications of the literature survey are specifically discussed with regards to the definition of the success criteria and the answers to the three main research questions defined in Chapter 1.

The literature survey helped define the context of the research project and provided background information that was used during data collection and analysis. It confirmed the assumptions made about the relevance of reusing knowledge for a product's success and indicated that research was still needed to understand how to take into consideration users' needs and organisational context whilst developing a knowledge management strategy.

The literature survey also highlighted the importance of:

- Defining the context in which knowledge transfer is analysed, including the phase of the knowledge lifecycle, type of knowledge transfer, characteristics of the industry and product.
- Defining the perspective adopted when analysing knowledge management.

The paragraphs below elaborate on the two points and relate them to the case studies that represent the core the research project.

#### ***Context of knowledge transfer***

The literature survey confirmed the need for further investigating the characteristics of service knowledge and how it is reused; this thesis aims to close this gap. The case studies that were selected to conduct this investigation were from the oil industry.

This choice had the following implications:

- Focusing on complex products, i.e. the drilling system, whose development process is characterised by the development of the different components in parallel (see Figure 3.9.c).
- Focusing on customised products: given the one-off nature of the drilling system, the prototype and testing phase is very limited compared to a mass produced product.

### ***Perspective adopted in the case studies***

The literature survey showed that a variety of approaches can be adopted when investigating knowledge and its transfer. The main approaches that influenced the case studies presented in this thesis are summarised below.

Knowledge schools. The literature survey indicated the importance of the definition of the perspective adopted when investigating knowledge. Research on knowledge from the engineering domain usually follows the “technocratic” perspective, with knowledge perceived as information that can be captured, stored, updated, etc. hence this was the approach initially adopted for the research project. However, the importance for the success of a knowledge management strategy of elements that go beyond IT tools emerged both from literature and from the first phases of the case studies. Hence, the approach adopted for researching the reuse of service knowledge was modified in order to also take into account other factors, such as communication flows between the different stakeholders.

Types of knowledge. The distinction between declarative, procedural and causal knowledge has been taken into consideration when developing the coding scheme used for analysing the knowledge relevant for service engineers and engineering designers. Declarative knowledge was further divided into: product, issue and function, as suggested by the ontology for classifying engineering knowledge proposed by Ahmed (2005).

Explicitness. The case studies focused on explicit knowledge, in the form of both personal and codified knowledge, rather than implicit knowledge.

Phases of knowledge lifecycle. The phases of the knowledge lifecycle investigated in the research project correspond to the mobilisation and diffusion phases in Birkinshaw’s framework (Birkinshaw and Sheehan 2002). In the analysed case studies service knowledge was available within the organisation; however the manner to distribute it to relevant stakeholders and reuse it in the most effective way is still to be defined.

Framework for knowledge transfer. The sender-receiver framework was selected for investigating how knowledge was transferred between stakeholders, as stakeholders from different backgrounds were involved in the analysis, namely service engineers and engineering designers.

### 3.8.1 Success criteria

In engineering design research the identification of success criteria is important to be able to evaluate the results of the research project, as already highlighted in Chapter 2. The literature survey suggests that a possible criterion for evaluating the success of the project, and in general of the reuse of service knowledge in an engineering context, is the enhancement in a product's quality and its performances during service. However, measuring a product's quality and performances is difficult in an industrial context and impossible within the timeframe of the research project. Measurable criteria to evaluate the effectiveness of the re-use of knowledge from the service phase of complex products could be:

- The number of engineering changes during the product lifecycle. A good management of knowledge across lifecycle's phases should reduce the number of changes to implement to the product after the design phase is concluded.
- Time to execute a service request. Better communication between designers and service engineers should reduce the time required to answer a service request.

### 3.8.2 Research Questions

*Research Question 1. What characterises the knowledge arising from the service phase of complex products? What aspects of knowledge from service are relevant for service engineers and engineering designers?*

This set of questions aimed to better define the research object that was investigated during the project and understand how the two actors taken into consideration, i.e. service engineers and engineering designers, perceived it. During the analysis of the case studies, the ontology describing engineering knowledge based on four root concepts (product, process, function and issues) proposed by Ahmed (2005) have been compared to the empirical evidence from the case studies in order to determine what types of knowledge are relevant for service engineers and engineering designers.

*Research Question 2. How is knowledge from service transferred within the service phase and across phases of the lifecycle?*

This question aimed to investigate the knowledge transfer mechanisms that were adopted for transferring knowledge within service and across the phases of the product's lifecycle. The frameworks describing knowledge transfer that are proposed in literature, particularly the sender-received framework for analysing asymmetric knowledge transfer, have been used to analyse the case studies.

*Research Question 3. How can the current situation be improved in order to obtain a systematic reuse of knowledge from service?*

The analysis of knowledge management applications in industry showed the main elements that need to be taken into consideration when developing a knowledge management strategy and identified the definition of a clear objective as critical for the success of a knowledge management strategy. Frameworks suggesting the steps to follow when developing a new strategy will be described in detail in Chapter 5, as they have been used to support the development of a model that facilitates the reuse of service knowledge.



### 3.9 Summary

This chapter identified the main research areas that are relevant for the project and provided an overview of the state-of-the-art research in those areas.

This literature survey showed that studies from different research domains agree on the importance of knowledge and its transfer. Management and organisational research sees the systematic reuse of available knowledge as a key factor for a company's success; psychology considers knowledge transfer as a fundamental mechanism for learning and skill acquisition; whilst engineering sees the transfer and reuse of knowledge as a means to improve existing products and services.

The success of a knowledge management strategy needs to be evaluated based, not on the amount of information that it allows stored in the repositories, but on the reuse of information in order to achieve a predefined objective, dependent on the specific case (e.g. improve the design of a product, faster training of new employees, etc.).

From the literature survey it appears that the most critical issue for the development of an effective knowledge management strategy is to capture the information that is needed to be reused. Hence, a knowledge management strategy needs to be adapted to the specific context and pursue a well defined aim.

The investigation of knowledge transfer in an engineering context is a field that needs further research as a better understanding of its mechanisms is crucial to develop a sound knowledge management strategy that fits the characteristics of a company. Given the increasing interest in knowledge generated in the later phases of a product's lifecycle, this thesis specifically focuses upon the analysis of the characteristics of engineering knowledge generated during the service phase and how it is transferred within and across the phases of a product's lifecycle, and aims to develop a model that supports the reuse of this knowledge.

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## 4. Descriptive study: reuse of service knowledge in the oil industry

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### 4.1 Introduction

This chapter illustrates the results from the descriptive study that investigated the different aspects of the knowledge generated during the service phase of complex, customised equipment. As anticipated in Chapter 2, a case study approach was adopted and three case studies (see Figure 4.1) were conducted within the oil industry in order to answer the following research questions:

RQ.1 *What characterises the knowledge generated during the service phase of complex products? What aspects of knowledge from service are relevant for service engineers and engineering designers?*

RQ.2 *How is knowledge from service transferred within the service phase and across phases of the lifecycle?*

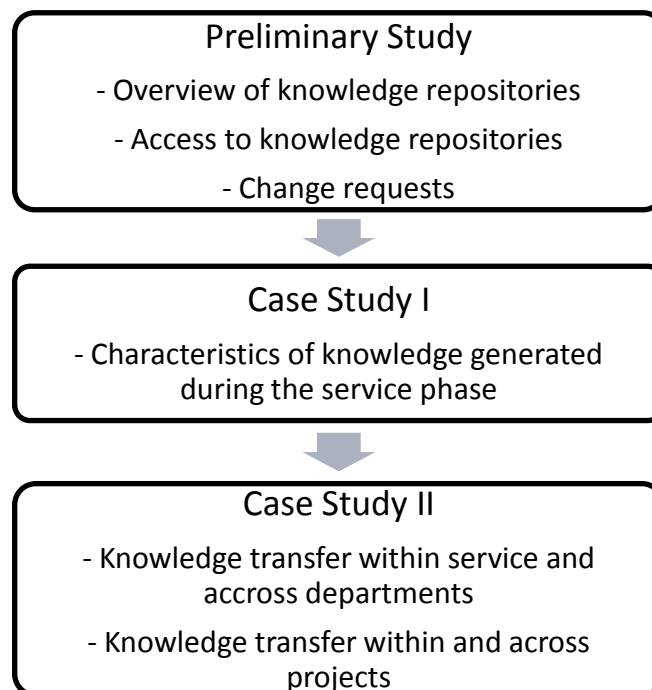


Figure 4.1 Case studies illustrated in this chapter.

The answers to these questions will be taken into consideration in Chapter 5, when a model to facilitate the reuse of service knowledge is proposed.

### ***Preliminary study***

The preliminary study, described in Section 4.2, was carried out at the collaborating company supplying drilling equipment for the oil industry in order to gain background information of the company in question and obtain an overview of the knowledge management system that was in use. This study is composed of three parts:

- Overview of the knowledge repositories, based upon document analysis, which investigated the repositories where information generated during the different phases of the equipment's lifecycle was stored;
- Analysis of the access to knowledge repositories, which investigated how knowledge repositories were used by service engineers and engineering designers through a survey;
- Analysis of documentation of changes, which provided a detailed analysis of change notifications, one of the most important types of documentation generated throughout the lifecycle of the drilling equipment.

### ***Case study I***

Case Study I, described in Section 4.3, investigated what characterises knowledge generated during the service phase and how this knowledge could be relevant for the different stakeholders. This study was conducted through a series of interviews with service engineers and engineering designers from the supplier of drilling equipment.

### ***Case study II***

Case Study II is presented in Section 4.4. It describes the knowledge transfer mechanisms used to transfer service knowledge both within the service phase and across phases of a product's lifecycle that emerged from the interviews at the supplier of the drilling equipment and at the drilling contractor.

This Chapter closes with Section 4.5, where the findings from the case studies are discussed and a summary of the results is provided.

## **4.2 Preliminary study**

The first phase of the research project focused on what information was available from knowledge repositories and how it was structured and used at the collaborating company, which supplies drilling equipment for the oil industry. After obtaining a general overview of the knowledge repositories and investigating how they were accessed by the different users, the analysis focused upon documentation of changes arising throughout the lifecycle of the drilling equipment. This choice of investigating in detail a particular type of documentation was motivated by the fact that the management of change requests is critical for the success of a product, as highlighted in the literature survey, and requires the involvement of engineering designers, no matter in which phase of the lifecycle a change arises.

### **4.2.1 Aims**

The preliminary study was carried out with multiple aims. Specifically:

- Gathering information about the company representing the main case study. This information represented the background knowledge upon which the subsequent phases of the project were grounded. For instance the information obtained was used to formulate relevant questions for the semi-structured interviews, which represented the core of the research project.
- Obtaining an overview of the knowledge repositories at the supplier of drilling systems, in order to understand which type of information was stored and how it was organised.
- Understanding how the different users, namely service engineers and engineering designers, approached the company's repositories.



#### 4.2.2 Methods

The methods for data collection adopted for carrying out the preliminary study are:

- Document analysis;
- Survey (i.e. structured interviews).

The general characteristics of these methods have been anticipated in Chapter 2, whilst the following sections describe how the methods have been applied to the case study.

##### *Document analysis*

Document analysis was chosen as a research method to obtain an overview of the knowledge repositories available at the collaborating company. This choice was motivated by the need to analyse the repositories in the first instance without any guidance or bias from people directly involved in their development or use.

A total of 16 repositories were taken into account and mapped against the content of the information stored and the criteria adopted for indexing the information; the list of the repositories taken into consideration is provided in Table 4.1. This analysis was carried out to obtain an overview of how codified information was organised at the company and the outcome was comparable to the impression of a new employee who approaches the knowledge repositories for the first time, without having any previous knowledge or receiving any training. The results from this analysis are reported in Section 4.2.3.

Table 4.1 Knowledge repositories taken into consideration during the preliminary study

<i>Database</i>	<i>Description</i>
Synergi	Database used to store HSE (Health, Safety, Environment) cases, in accordance with the industry's regulations
Frames	Set of databases used to store design information
CCN (Construction Change Notification)	Database part of frames used to report changes
SAP	Application used as organisational support, e.g. to assign a case number, define order, store documents.
SPS (Share Point Service)	Common platform used to share information within the organisation.
NCR (Non- Conformance Report)	Folder in SPS where product non-conformances, mostly involving suppliers, are stored.
VOR (Variation Order Request)	Folder in SPS where the client's changes to the original order are stored
Requirement list	Folder in SPS with product specification
Project folder	Folder in SPS with information related to a specific project (e.g. emails to clients and contractors, contracts)
PEM (Project Execution Model)	Set of procedures describing how to manage projects
Organisation chart	Database with details of the employees
WOSS	"Super-database" used to search for information from different sources
MIPS	Material Management systems used to track the progression of a project
HSE Alerts	Documents sent to the clients to inform them about HSE severe issues that could be relevant in a number of rigs and the actions needed to correct them. A prompt response is generally required.
HSE Bulletins	Documents sent to the clients to inform them about HSE issues that could be relevant to a number of rigs.
Product Bulletins	Documents sent to the clients to inform them about recent improvements on a product.

### Data analysis

Available documentation stored in knowledge repositories was mapped against its content and the indexing criteria. The picture emerging from the analysis was

compared to knowledge that has been found relevant in the engineering domain by previous research studies (Ahmed 2005).

The findings from the analysis of the repositories, which will be described in detail in the next section, were presented to the company for validation and to obtain insights on the rationale behind the configuration of the knowledge management systems.

### ***Survey***

After analysing the knowledge repositories available at the collaborating company, a questionnaire was distributed among service engineers and engineering designers to investigate how the two groups approached the different repositories. The survey aimed to understand: (1) what type of information was most relevant for the two groups; (2) how each group commonly stored and retrieved information and (3) where information was stored and retrieved. A total of 63 questionnaires were collected, as illustrated in Table 4.2. The text of the questionnaire is reported in Appendix 1.

Table 4.2 Number of questionnaires collected.

	<i>Service engineers</i>	<i>Engineering designers</i>
No. of questionnaires	40	23

### **Data analysis**

The answers, regarding type of information stored and retrieved, knowledge repositories accessed and search criteria utilised, were grouped according to the two groups of participants among which the questionnaire was distributed:

- Service engineers
- Engineering designers.

The results from the two groups were compared quantitatively, in order to investigate similarities and differences in the way service engineers and engineering designers accessed information.

### ***Change requests***

After having obtained an overview of the information that was stored in the company's repositories and how it was used, the analysis focused in detail upon documentation of changes. This type of documentation is of particular relevance in the context of this research, as how change requests arising throughout a product's lifecycle are managed directly impacts:

- The success of the product itself, due to the high cost of the implementation of changes in the later phases of the lifecycle (Carter and Baker 1992, Terwiesch and Loch 1999);
- The improvement of the next generation of products.

Additionally the management of requests for change from the later phases of a product's lifecycle requires collaboration between service engineers, requesting and eventually implementing the change, and engineering designers, evaluating the case and proposing the solution.

Documentation about changes was available at the collaborating company in the form of Construction Change Notifications (CCNs). CCNs included a description of the case and a set of metadata representing the criteria for indexing and retrieving documents. These criteria included type of product, employee assigned to the case, motivation, status, and phase of the lifecycle.

### **Data analysis**

Two datasets of 1169 and 451 change reports respectively were analysed in relation to the number of reports issued from the different phases of a product's lifecycle and the motivation for change. The criteria taken into account while analysing the change reports were:

- The phase of the lifecycle in which they were generated;
- The motivation of change.

Figure 4.2 illustrates the three phases of the lifecycle of the equipment that were used for indexing the reports: (1) design phase; (2) installation and commissioning phase and (3) service phase. Manufacturing was not included as it was outsourced to

suppliers; issues arising during this phase resulted in a complaint against the supplier through a Non-Conformance Report and not in a Construction Change Notification.

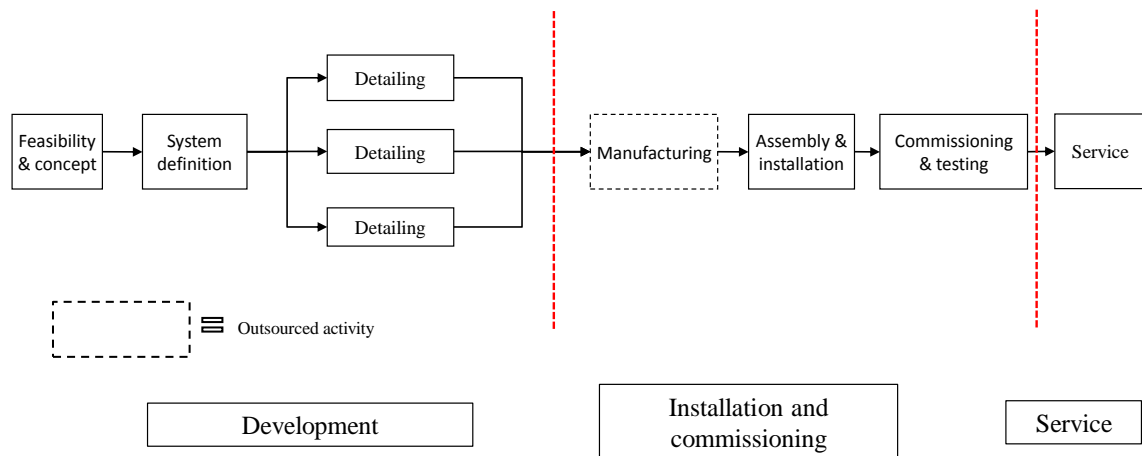


Figure 4.2 Changes arising throughout the lifecycle of the equipment were indexed by the company against three phases: (1) design phase; (2) installation and commissioning phase and (3) service phase.

The motivations of change adopted by the company to index the reports were:

- Product improvement
- Fault correction
- Carry over work
- Variation order request
- Parameter tuning
- Temporary change

Whilst the first two motivations, *product improvement* and *fault correction*, are general motivations for changes, the other criteria used to index a case against its motivation were specific for the selected industry, as they were strictly related to the customised nature of the drilling equipment.

The two data sets analysed consisted of:

- 1) A total of 1169 reports of change related to the same type of equipment. Those reports were analysed in order to investigate the distribution of the reports and the main motivation of change at the different stages of the lifecycle of the selected equipment. The equipment selected for this analysis was crucial for

the drilling process as its function was to transmit the torque to the drillstring. Since the equipment had been operating for six years at the time when the analysis was carried out, a considerable amount of documentations from the service phase was available.

- 2) A total of 451 reports of change from four rigs, part of the same series (e.g. having the same drilling equipment installed) and delivered with a 6 month delay between each rig, were analysed in order to detect trends regarding the distribution of changes within a rig's lifecycle and across the four rigs (see Figure 4.3). The lifecycle of each rig was divided into stages covering a 6 month period. The first stage corresponded to the engineering phase, the second and third stages covered installation and commissioning, and the fourth stage corresponded to the rig entering into operation. At the time of data collection, the first three rigs were in operation, while the last one was still in the installation and commissioning phase, hence the data from the later stages are available only for the first rigs of the series. Number and motivation of changes characterising analogous stages of lifecycle of the rigs were investigated and compared.

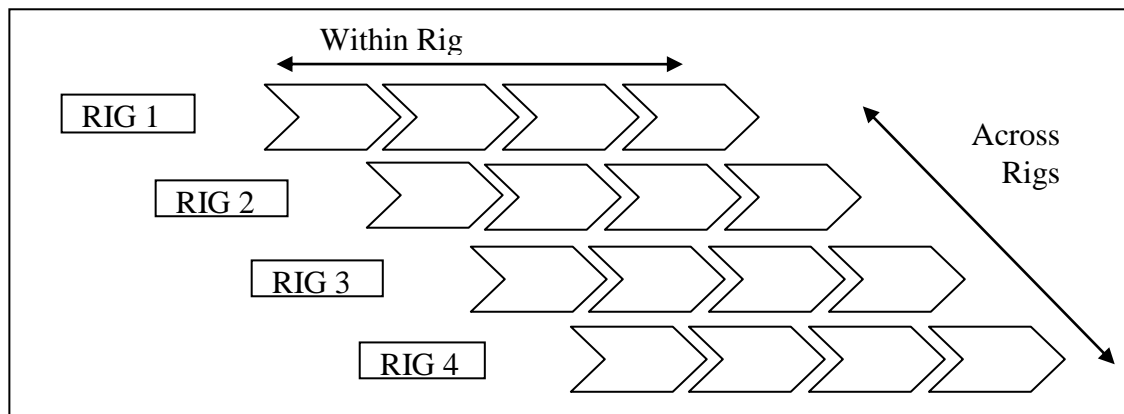


Figure 4.3 Changes were investigated within a rig's lifecycle and across rigs from the same series.

#### 4.2.3 Results

This section illustrates the results from the preliminary studies. First, an overview of the knowledge repositories at the collaborating company is provided; then the results of the survey investigating how service engineers and engineering designers accessed

the available information are presented. Finally, the documentation of changes is investigated in more detail and the results of this investigation are described in the last subsection.

### ***Overview of knowledge repositories***

#### Structure of the repositories

The analysis of available documentation showed that information was fragmented across repositories. A total of 16 repositories for storing technical information were analysed in order to investigate what information was available and how it could be retrieved.

Several factors influenced the choice of the repository where information was stored, the main factors were:

- Type of information. Most of the repositories were dedicated to a specific type of information, e.g. *product*, *process* or *issues*.
- Time. The repositories were changing over time; hence information captured at different points in time was stored into different repositories.
- User group and phase of the development process. Different repositories were used by the different departments and in the different phases of the development process.
- Project. Documentation from each project was structured differently, depending on the individual approach of the project manager and the characteristics of the project itself.

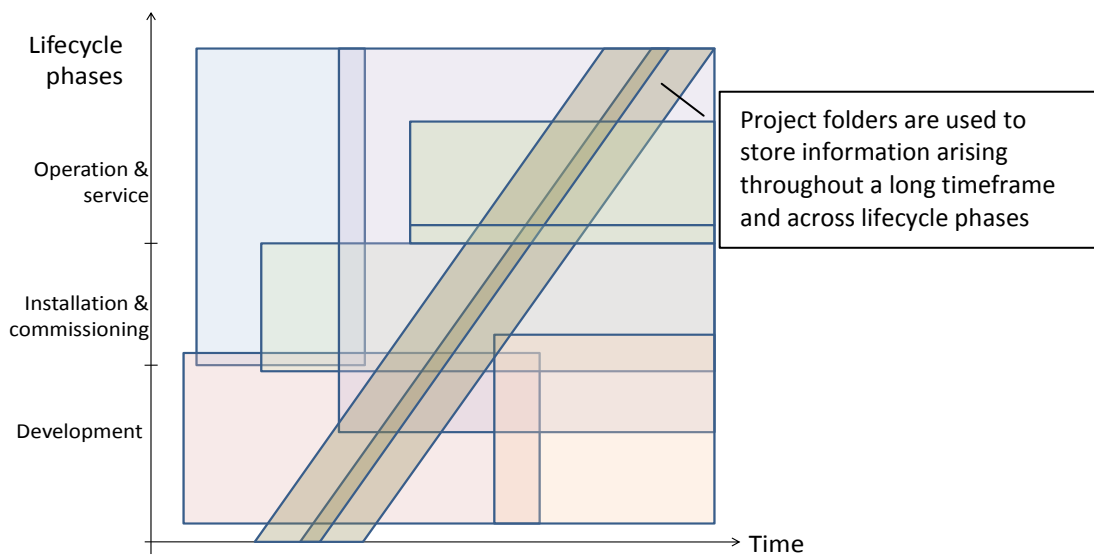


Figure 4.4: Each shape in the figure symbolises a repository. The axes are time and phases of the product lifecycle respectively. The choice of the repository used to store and retrieve information was influenced, besides the type of information handled, also by: (1) the time when the information was generated, (2) the phase in the product's lifecycle, (3) the project that the information was related to. The squares and rectangles in the figure represent repositories for storing a specific type of information during a defined phase of the lifecycle and were used for a limited timeframe, while the parallelograms represent repositories for storing information from a single project and covered all the phases of the lifecycle of that project (e.g. project folders).

An exemplification of the situation available while seeking for information is illustrated in Figure 4.4, where each shape represents a repository. In order to retrieve information about, for instance, the installation and commissioning of a given piece of equipment, it was necessary to:

- Define the type of information of interest (e.g. *issue*, *process*).
- Select relevant projects.
- Define the period in time when the documentation was expected to be generated, and consequently identify the repositories used to store information about installation and commissioning phases at that time.



Additionally, searching across repositories was necessary in order to obtain a complete overview of a topic, as it was not possible to obtain all the information from one repository and relevant documentation could be available in various forms and stored in different repositories (e.g. manuals, procedures, emails, bulletins).

The dialogue with the company, that was carried out to validate the results, suggested that the company was already aware of the difficulties in retrieving information scattered across repositories; a first attempt to solve the problem entailed the implementation of a shared interface aiming to present information stored in different systems. However, differences in the structure of the documents and in the indexing criteria that were adopted in the various repositories limited the effectiveness of the system.

Moreover, from the validation of the results it emerged that, besides the repositories accessible at organisational level, a number of other repositories, not taken into account in the analysis, were available at the company. These repositories addressed the needs of closed user groups and were characterised by restricted access. The motivations for creating repositories only accessible to a limited number of employees were various, for instance: (1) financial, motivated by the high cost of software licenses; (2) related to users' competences, as some tools required specific skills in order to be used in an effective way (e.g. SAP); (3) related to shared interests among the users (e.g. employees working in the same area or involved in the same project etc).

### Indexing criteria

The 16 repositories taken into account in the investigation were analysed with regard to the indexing criteria implemented to search for documentation, in order to understand how users could access documentation. A total of 19 indexing criteria were adopted in the 16 repositories. However, 9 of the criteria were used only in one repository, whilst the most common indexing criterion, the *project number*, was used in 11 of the repositories. The second most common criteria, *product* and *date*, were implemented to index documentation in only 5 repositories. Moreover, they were only

secondary criteria in some of the knowledge repositories, where the first compulsory step was to search for information by *project* and it was only possible to select the relevant *product* or *date* afterward, as a secondary criterion. This organisation of the repositories impeded the retrieval of information about, for instance, a product across different projects, as the selection of the *project* of interest was the first, necessary step to retrieve information.

### Summary of the findings

The main findings from the analysis of the company's repositories are summarised as follows:

- Information was spread in different repositories and searching across repositories was necessary to obtain a complete view of a topic.
- Repositories were addressed to specific user groups and often had restricted access.
- Repositories captured information from specific phases of the product's lifecycle, and were continuously evolving.
- Organisation of documentation was dependent on the project.
- No search criteria were common across repositories.

These findings suggest difficulties in reusing documentation, particularly when the retriever is not familiar with the relevant knowledge repositories, as in the case of a new employee or a person from a different department.

### ***Access to knowledge repositories***

After having mapped the repositories available at the collaborating company and the criteria adopted to index the documents, a questionnaire was distributed among service engineers and engineering designers in order to understand how the two user groups accessed the available information.

### Type of information stored and retrieved

The first set of questions focused upon *what* type of information was stored and retrieved by the two groups. The distribution of the answers is shown in Figure 4.5

and Figure 4.6 and suggests that both the groups contributed to developing and storing *project documentation* and *procedures*; however part of the information stored in the repositories by service engineers and engineering designers was influenced by their specific field of competences, with engineering designers making and subsequently storing *drawings*, and service engineers reporting their work through *service reports*. Additionally, whilst engineering designers tended to store information in the form of *procedures*, *project documentation* and *drawings* (each type was stored by more than 60% of the engineering designers), information stored by service engineers embraced a wider range of formats.

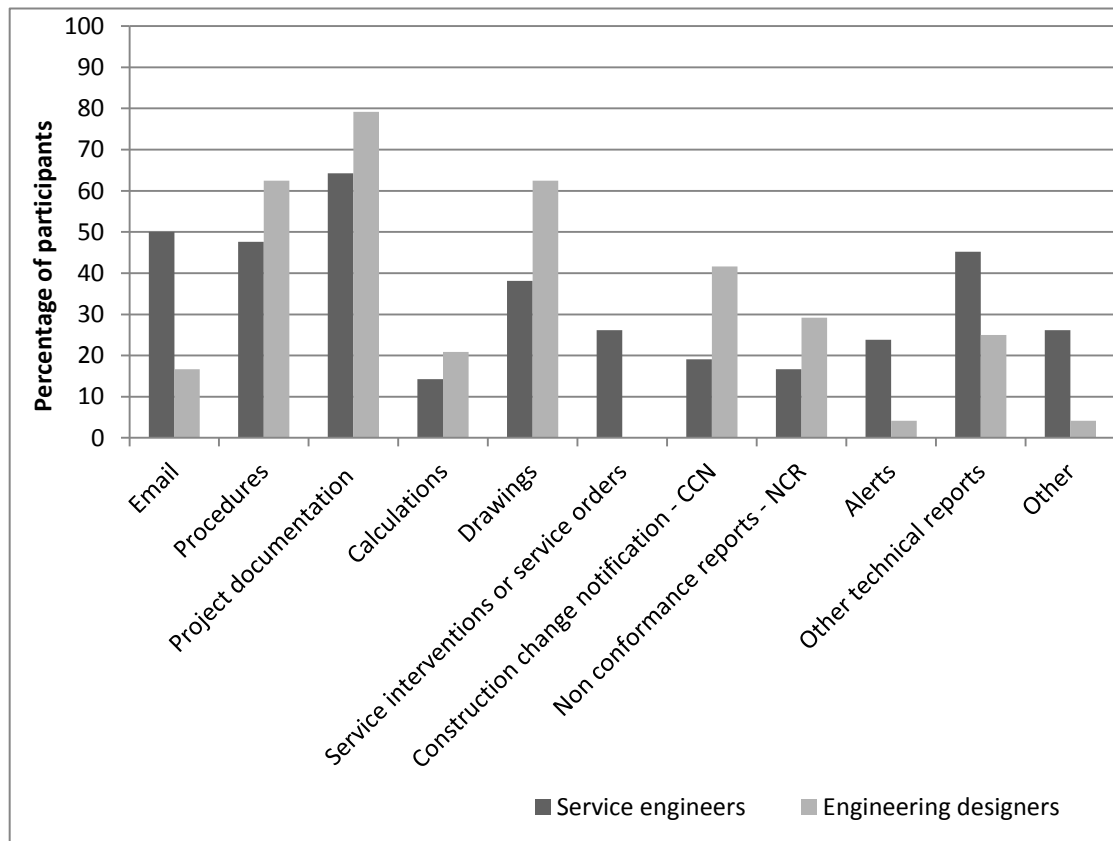


Figure 4.5 Information stored by service engineers and engineering designers.

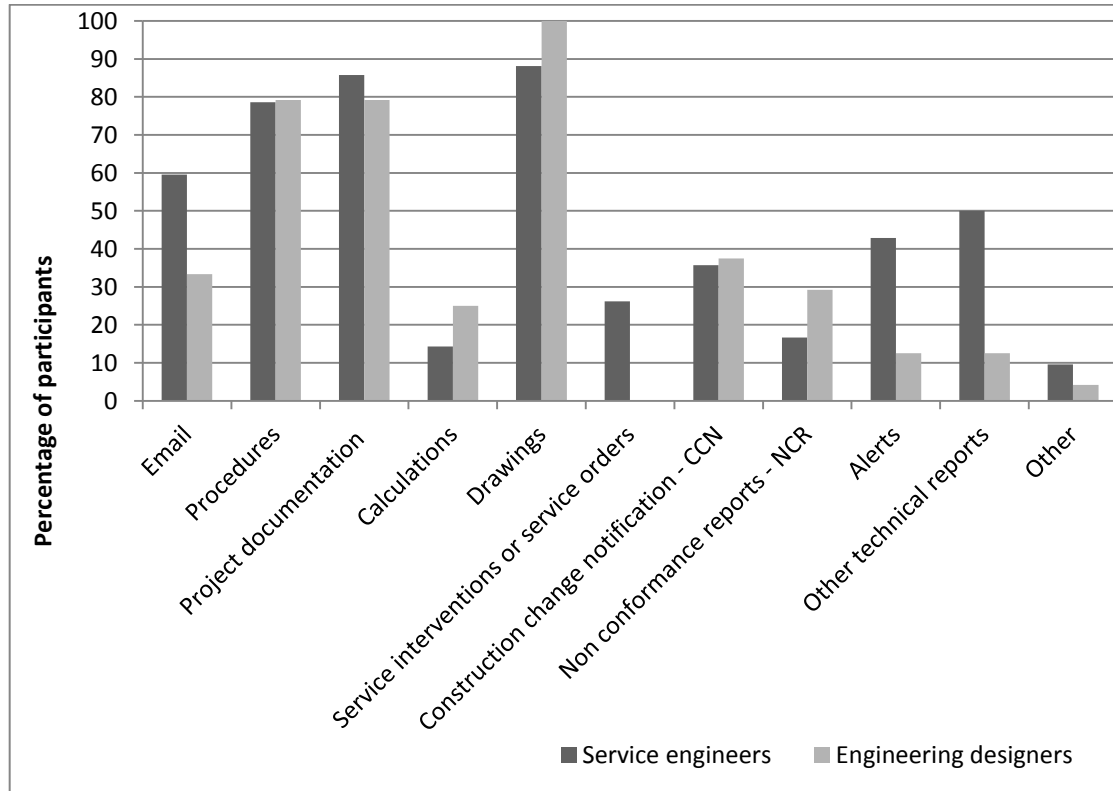


Figure 4.6 Information retrieved by service engineers and engineering designers.

Comparing Figure 4.5 to Figure 4.6, it appears that, as expected, the number of service engineers and engineering designers retrieving information was higher than the number of those storing it. Additionally, Figure 4.6 shows that both service engineers and engineering designers mainly retrieved the same types of information: information about *products*, in the form of *drawings*, was the main information retrieved from the repositories, followed by *procedures*, describing the company's standard processes, and *project* documentation. These types of information were generally stored in the repositories by engineering designers, meaning that information stored by the engineering designers was of interest, not only within the design department, but also to service engineers. On the contrary, the documents arising from the lifecycle of the drilling equipment and stored in the repositories by service engineers (e.g. reports of service interventions, alerts and other technical reports) were only to a minor extent retrieved by designers; hence this type of information was relevant mostly for service engineers. This suggested that making information from the service phase available through knowledge repositories is not

sufficient to ensure that engineering designers will reuse it; supplementary actions, such as actively pushing relevant information to engineering designers or explicitly mentioning the reuse of information from service in the company's procedures, are also required.

Documentation about *issues* was available in various forms, depending on the type of issue involved and the phase of the lifecycle when the issue arose. During manufacturing and assembly, when both engineering designers and service engineers were involved, issues were mostly captured as: (1) non conformances, when the product did not fulfil the requirements; (2) change notifications, when an issue was recorded in terms of the action performed to correct it. Once the rig entered operation, documentation on service cases was captured into technical reports after the closure of the cases; this type of documentation was primarily written to inform the client of what was done, and it was not used for internal purposes, e.g., to inform the headquarters of the progression of a service case.

A third type of documentation about issues was represented by alerts and bulletins, aiming to inform clients about issues that might pose a risk to the overall functioning of a rig or the safety of the crews. These reports included indications on the action to perform to prevent the problem from occurring.

The percentage of participants retrieving information about issues was not remarkably higher than the percentage of participants storing it, contrary to what was noticed for other types of information. This trend was more evident in the case of engineering designers, as the percentage of engineering designers retrieving documentation about issues was equal to, or lower than, the percentage of engineering designers storing the same type of documentation.

### Type of information searched

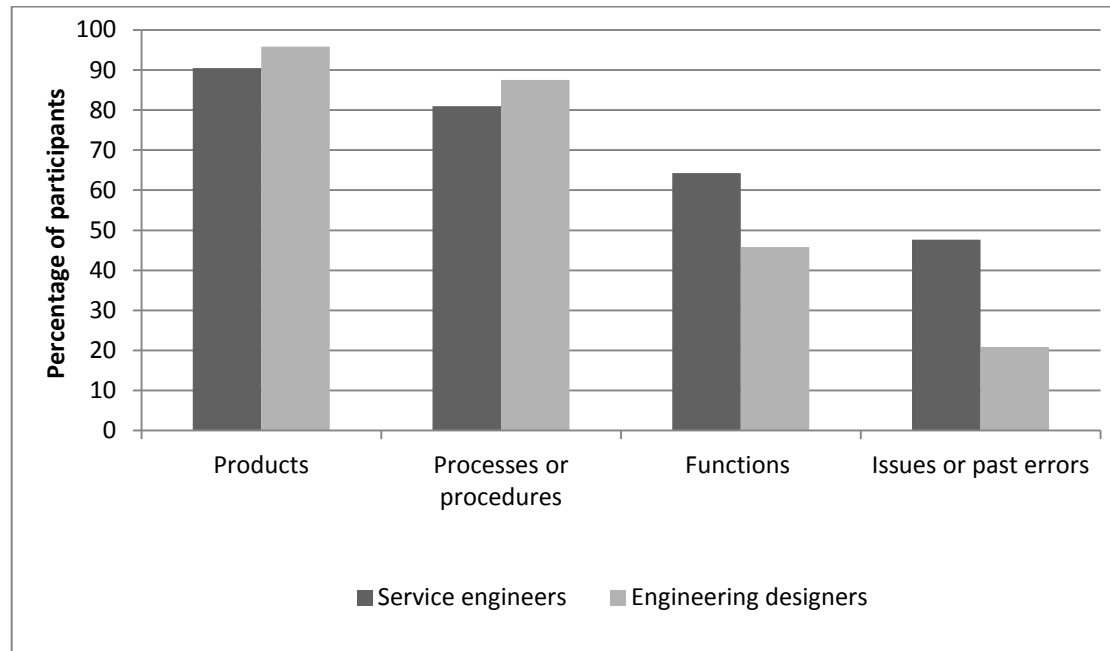


Figure 4.7 Type of information searched by service engineers and engineering designers.

After investigating the type of information that was captured and retrieved through the company's repositories, the survey focused upon the type of information service engineers and engineering designers searched for (see Figure 4.7). This investigation was based upon the ontology describing the types of knowledge relevant for engineering designers proposed by Ahmed (2005). The results confirmed the relevance of information about *products* and *procedures*; however, the answers also showed discrepancies between what the participants searched for and the information available. Information about *functions* was relevant for almost 50% of the engineering designers and more than 60% of the service engineers but the system did not allow retrieving information searching by function. Information about *issues* was sought by less than 50% of the service engineers and around 20% of engineering designers; this result is in disagreement with the fact that more than 30% of the designers retrieved information on changes and non-conformances and suggests the need for structuring this information in a different way in order to facilitate its reuse.

The survey described in this section was designed as part of the initial explorative study and based upon categories from literature. This explains why information about

*projects* was not included among the options. The importance of this category emerged only in the subsequent stage of the research project, after the questionnaire had already been distributed. Due to time constraints and practical impediments, it was decided not to redistribute a revised version of the questionnaire that included *projects* as an option.

#### Search criteria used

As emerged from the study investigating the knowledge repositories available at the company, the documentation stored was indexed against a number of search criteria; however none of these criteria were implemented across all the repositories.

Table 4.3 illustrates the search criteria used by service engineers and engineering designers and suggests which of them should be widely implemented across repositories in order to facilitate the retrieval of information, as they were extensively used by both the groups. For instance *product*, *project* and *part number*, were used by at least 70% of both service engineers and engineering designers.

Table 4.3 The 10 most popular search criteria to retrieve information.

<b><i>Search criteria</i></b>	<b><i>Percentage of service engineers</i></b>	<b><i>Percentage of engineering designers</i></b>
Product	90	92
Project	83	96
Rig	79	33
Document number	67	92
Part number	71	75
Type of equipment	57	38
Tag number	24	42
Location	24	13
Control system	12	25
Employee number	19	13

This analysis of the criteria used for indexing the available information also suggests that information about *product* was made accessible at different levels, in order to answer to the needs of the different users, as shown in Figure 4.8. The data reported in Table 4.3 indicate that service engineers and engineering designers approached information about *product* in two different ways. The first tended to search for information about *product* at a general level (e.g. *rig*, *type of equipment*), while the latter were more prone to retrieve information at the component level (e.g. *part number*, *tag number*). This difference in the way service engineers and engineering designers access information about *product* needs to be taken into consideration when selecting the criteria for indexing documents, as the criteria adopted should reflect the need of the targeted users.

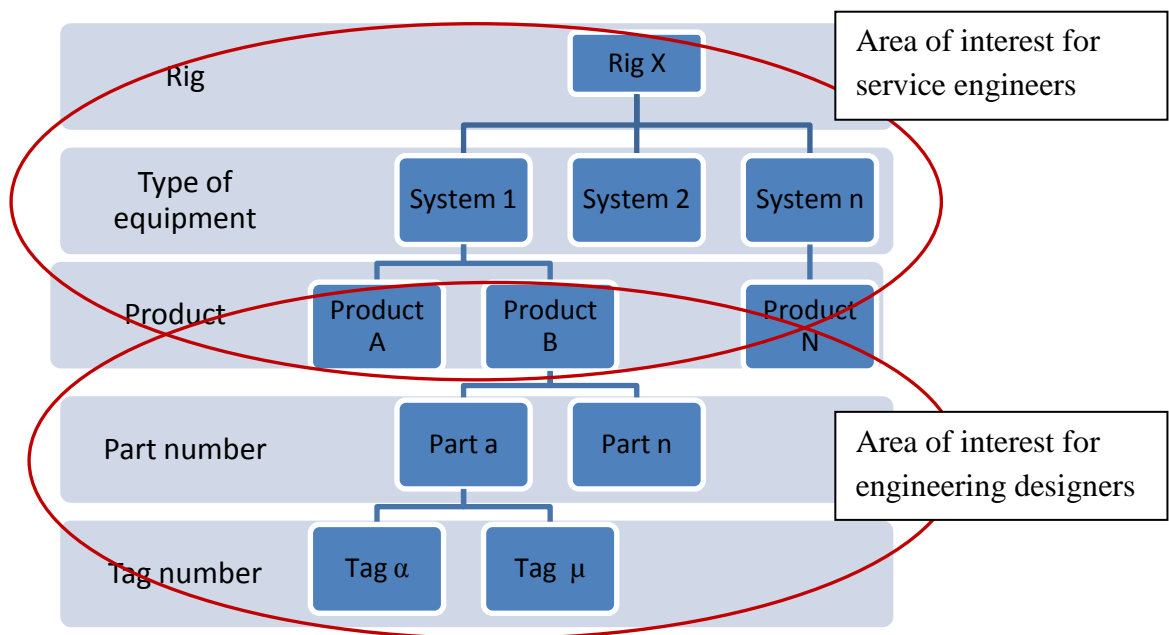


Figure 4.8 Different ways of accessing information about *products*.

### Summary of the findings

The main findings from the analysis of the survey are summarised as follows:

- Engineering designers and service engineers were interested in different types of information.
- Information about issues was not extensively retrieved by service engineers or engineering designers.



- Engineering designers and service engineers tended to use the same repositories both to store and retrieve information.
- Engineering designers did not search for documentation from the service phase.
- The most common search criteria used to retrieve information were *product*, *project* and *part number*.
- Information about *product* was accessible at different levels of detail. Service engineers searched for information about product at a general level (e.g. rig, type of equipment), whilst engineering designers searched for this type of information at a more detailed level (e.g. part number).

The analysis of the survey that investigated how service engineers and engineering designers accessed information stored in repositories provided a better understanding of how the different user groups approached knowledge management tools. This understanding was used to formulate appropriate questions during the semi structured interviews.

Additionally, the survey showed that more than 35% of both service engineers and engineering designers retrieved documentation on changes (CCN). Hence this type of documentation has been investigated more in detail and the results are presented in the following section.

### ***Example of documentation: change requests***

The present section describes the characteristics of the change documentation available at the collaborating company (i.e. construction change notifications, or CCN, as this type of documentation was called in the specific case). The choice of focusing upon this type of documentation was motivated by the fact that the survey described in the previous section showed that construction change notifications were the type of information arising throughout a product lifecycle that was more extensively used by both service engineers and engineering designers. Additionally, the importance of information of changes is not specific to the case study taken into consideration; the literature survey presented in Chapter 3 indicated that a sound

management of engineering changes is a critical factor for the success of a product in a multitude of contexts.

The main purposes for generating change documentation at the collaborating company were:

- To capture information about the change in a structured way, in order to inform the stakeholders involved in the change process, and for future reuse;
- To request approval, as changes arising from the later phases of the lifecycle needed to be formally captured and fed back to designers in order to be approved.

Hence, change documentation represented a way of transferring information across departments in a codified manner.

This study analysed change reports in relation to the phase of the lifecycle when the documentation was issued and the motivation of the change. The methods used to analyse the case study have been described in detail in Section 4.2.2. The incompleteness of the available documentation was one of the main issues that emerged during data collection, as only 55% of the reports were indexed against the phase of the lifecycle when they were issued; furthermore, only 66% of these reports were also filed against the motivation of change.

The analysis of change documentation first investigated the documentation related to a specific type of equipment installed in different rigs and secondly the distribution of changes arising from a series of four similar rigs. This second study aimed to understand whether a reduction of the number of changes occurred from the first rig to the subsequent ones. If that was the case, it would mean that some type of transfer of information occurred across the rigs, either through personalisation or codification strategies.

#### Distribution of changes for the same type of equipment

The first study analysed the changes relating to a type of equipment, which was identified as crucial for the drilling process. Table 4.4 shows the distribution of changes throughout the lifecycle of the equipment, from the design to the service

phase: 55% of changes arose during installation and commissioning, 30% during the service phase, while only 15% of the reports were issued during the design phase. The number of changes arising throughout the different phases of the equipment's lifecycle suggested that the change management process needed to be coordinated at organisational level in order to feed the information of changes arising from the later phases of the lifecycle to the engineering designers.

Table 4.4 Number of changes at different phases of the lifecycle of the drilling equipment.

<i>Phase of the lifecycle</i>	<i>No. of reports</i>	<i>Percentage (%)</i>
Design	100	15
Installation and Commissioning	356	55
Service	194	30

Table 4.5 Motivation of change for each phase of the lifecycle of the drilling equipment.

Main motivations of change	<i>Lifecycle phases</i>		
	<i>Design phase</i>	<i>Installation and commissioning phase</i>	<i>Service phase</i>
	Improvement (66%)	Fault Correction (55%)	Fault Correction (45%)
	Fault Correction (26%)	Improvement (29%)	Improvement (39%)
	Carry over work (4%)	Carry over work (10%)	Parameter tuning (11%)
	Variation order req. (2%)	Parameter tuning (4%)	Variation order req. (4%)

Table 4.5 illustrates the main motivations of change in the different phases of the product's lifecycle and shows that they vary from phase to phase. Product's *improvement* was the main motivation of change in the design phase, whilst *fault correction* was the main motivation during installation and commissioning, and service. This suggests that designers may not have been aware of issues arising during

the later phases of a product's lifecycle; hence, these issues were not always considered during the design phase. The other motivations of change, i.e. *carry over work*, *variation order request* and *parameter tuning*, were related to the customised nature of the drilling equipment; they had only a limited impact on the total number of change requests.

Changes motivated by *carry-over work* were changes to the original project plan that were implemented in order to respect the delivery schedule agreed with the client (e.g. a task supposed to be accomplished in the design phase was carried over to commissioning so as not to cause a delay to the whole project).

*Variation order requests* led to changes to the original design of the equipment in order to fulfil new requests from the client.

*Parameter tuning* led to changes in the default configuration and settings of the equipment in order to adapt it to the environment where it was going to operate.

The distributions of the motivation of changes in the design phase and the installation and commissioning phase were compared through a  $\chi^2$  test to verify whether the two could be considered different also from the statistical point of view. The results confirmed that the two distributions were significantly different, with  $\chi^2(4)=67$ ,  $p<0.0001$ ; hence the motivation of change characterising the two phases of the lifecycle did not follow the same distribution. A similar result came from the comparison of the motivation of change characterising installation and commissioning and service phases: the result of the  $\chi^2$  test was:  $\chi^2(4)=22$ ,  $p=0.0002$ ; this value also indicates that the difference between the two distributions was statistically significant. The significant difference in the distribution of the motivation of change throughout the lifecycle of the drilling equipment indicates that there was a correlation between the phase of the lifecycle when the change arose and the motivation of change.

These findings from the analysis of change documentation are consistent with a more general, yet wider, survey carried out with 171 companies within the German Manufacturing Industry. The survey aimed to understand how and when companies identify design flaws and found that only 5% of design flaws were identified during

the development phase (Gries, Gericke et al. 2005). The majority of design flaws were reported by customers or users (around 36%), followed by flaws detected during manufacture and assembly, and flaws detected as a result of warranty claims (around 25% each). A design flaw is not the only motivation for change to the design; however, the similarity between the two cases is still relevant.

#### Distribution of changes in the case of similar rigs

The distribution of the number of changes and the motivation of change were then investigated for a series of four oil rigs to be completed with a 6 month delay between each rig. The rigs, from a construction point of view, were considered copies (i.e. the same type of equipment was installed), as the intention of the manufacturer and the client was to reuse the rig design and the experience arising from installation and commissioning of the first rig in the subsequent rigs.

The reports of changes arising throughout the lifecycle of the four rigs were analysed quantitatively. The trends emerging from the analysis of the number of changes and their motivation were investigated:

- Within each rig, throughout its lifecycle;
- Across rigs, comparing corresponding stages.

The number of changes arising throughout the lifecycle of each of the four rigs is shown in Table 4.6.

Table 4.6 Distribution of the number of changes throughout the lifecycle of the four rigs part of the same series (“-“ indicated data that were not available at the time of the analysis).

<i>Stages</i>	<i>No. of Changes</i>			
	Rig1	Rig2	Rig3	Rig4
1st Stage	22	5	5	5
2nd Stage	79	8	10	10
3rd Stage	32	26	29	23
4th Stage	48	35	24	-
5th Stage	37	25	-	-
6th Stage	28	-	-	-
Total number of changes for each rig	246	99	68	38

The reduction of the number of changes between the first and the second rig was evident, particularly in the early phases of the lifecycle, when the number of changes dropped 75% and 90% respectively. The distribution of number of changes arising from the lifecycle of the first and the second rig of the series were compared through a  $\chi^2$  test to verify whether the two were significantly different from a statistical point of view (see Appendix 3 for a description of the  $\chi^2$  method). The results confirmed a significant difference between the two cases, with  $\chi^2(4)=116$ ,  $p<0.0001$ , hence the number of changes arising from the two rigs did not follow the same distribution. On the contrary, the distributions of the number of changes in the later rigs of the series were not significantly different. For instance, the result of the  $\chi^2$  test that compared the data from the second and the third rig was  $\chi^2(3)=3.98$ ,  $p=0.26$ . This verifies the correlation between the two distributions. The difference in the distribution of the number of changes between the first rig and the others indicates that experience was transferred across the rigs. The number of changes from the later rigs of the family followed the same pattern of the changes emerging in the second rig and suggested that a further reduction of the number of changes in the last rigs was not likely to happen. One explanation of this trend is that in a customised industry the testing phase is limited, hence the faults are detected throughout the lifecycle of the first rig and then the solution transferred across rigs.

The reduction of the number of changes across rigs peaked in the first two stages, corresponding to the development and installation phases, while it was more limited in the later stages. This trend could be explained by the fact that the mechanisms adopted at the company for transferring experience across rigs were more suitable for the early phases of the product's lifecycle than for the later ones.

Table 4.7 shows the motivations of change in each rig and how it was distributed throughout the rig's lifecycle. On the one hand, the distribution of the motivation of change throughout the lifecycle of the first rig was comparable to the one described for one type of equipment installed in different rigs (see Table 4.5): *product improvement* was the main motivation for change in the first two stages of product

lifecycle, that corresponded to the design phase, whilst *fault correction* motivated changes from the 3<sup>rd</sup> and 4<sup>th</sup> stages, that corresponded to installation and commissioning. The similarities between the two distributions were confirmed by two  $\chi^2$  tests comparing motivations for change in the design phase and in the installation and commissioning phase (the different length of the service phase in the two cases did not allow a comparison of changes from service). The results were  $p=0.067$  for the design phase and  $p=0.111$  for the installation and commissioning phase; this confirming that the differences between the two cases were not statistically significant.

Table 4.7 Number of change reports for the four oil rigs of the same series. The reports have been grouped according to the motivation of change and the stage of the lifecycle when they were issued. ("R1": rig1; "R2":rig2; etc.; "-" indicated data that were not available at the time of the analysis).

STAGE	<i>Fault Correction</i>				<i>Improvement</i>				<i>Carry-over Work</i>				<i>Others</i>				<i>Not Indexed</i>			
	R1	R2	R3	R4	R1	R2	R3	R4	R1	R2	R3	R4	R1	R2	R3	R4	R1	R2	R3	R4
1	8	2	3	1	13	0	1	0	0	0	0	3	1	0	0	0	0	3	1	1
2	26	5	4	1	46	2	0	3	0	1	6	3	0	0	0	2	7	0	0	1
3	18	9	9	7	5	1	6	11	2	14	4	3	1	1	2	0	6	1	8	3
4	22	8	9	-	8	14	9	-	4	5	1	-	6	3	0	-	8	5	4	-
5	12	7	-	-	6	13	-	-	4	1	-	-	2	0	-	-	13	4	-	-
6	4	-	-	-	0	-	-	-	1	-	-	-	3	-	-	-	20	-	-	-

On the other hand, differences emerged between the motivation for changes in the first rig of the series and the subsequent ones, as confirmed by  $\chi^2$  tests comparing the distribution of changes of the first and the second rigs, that resulted in  $p<0.0001$  for all the phases of the lifecycle of the rigs. In the later rigs of the series, the distribution of the motivation of change was reversed. *Fault correction* motivated changes in the early stages, whilst further in the lifecycle changes were mainly implemented to *improve the product*. This suggests that faults were detected earlier in the last three rigs of the series due to the experience that emerged from the first rig, while the

suggestions for improvement were influenced by the preferences and ideas of the engineers involved in the specific rig, hence more difficult to transfer across rigs.

Besides *fault correction* and *product improvement*, another motivation of change relevant for the analysed case was *carry-over work*. This motivation was connected to the type of industry investigated, as the development of customised equipment dealt with issues related to time constraints, determined by the contract with the client; a change to the initial project plan was sometimes needed in order to respect the delivery times. Changes related to planning became more relevant in the later rigs of the series, as *carry-over work* was one of the main causes of changes in the last three rigs. This indicates that while knowledge about the *product* was successfully transferred across rigs, knowledge about how to manage a *project* and respect its planned schedule was more difficult to transfer across rigs, despite them sharing the same design. The issue of how to reduce *carry-over work* in a customised industry is related to the general topic of how to efficiently organise not only declarative knowledge but also procedural knowledge. This is crucial for a customised industry as, while the characteristics of a product may change from project to project, the process followed to develop each product from design to delivery should be common across projects.

### Summary of the findings

The main findings from the analysis of change documentation are summarised as follows:

- The installation and commissioning phase resulted in the most critical phase with regard to changes, followed by the service phase.
- Changes arising in the early phases of the lifecycle were mainly motivated by product improvement, whilst changes in the later phases were primarily implemented to correct a previous fault.
- Information about faults was transferred across similar rigs and this led to a reduction of the number of changes motivated by *fault correction* in the later rigs of the series. Difficulties in transferring information about the project (in order to



avoid *carry over work*) and ideas for improvements across similar rigs resulted in a limited reduction of the number of changes whose motivation was product *improvement* or *carry over work*.

This study confirmed the importance of improving the reuse of information from the later phases of a product lifecycle, as those phases were the ones in which the highest number of change requests, particularly motivated by fault correction, were generated. Since the number of changes to a product, particularly during the later phases of its lifecycle directly impact its success, it is critical for a company to be able to promptly detect faults in a product's design and avoid their reoccurrence in other products.

#### 4.2.4 Discussion and implications

The three studies described in the previous sections, constituting the preliminary investigation, focused upon the information captured in repositories, hence investigated only one aspect of what constitutes a company's internal knowledge, not taking into account the personal expertise of the employees or knowledge that is transferred without the generation of any type of document. These aspects of knowledge and knowledge transfer were investigated through semi-structured interviews and the results are illustrated in Sections 4.3 and 4.4.

Hereby the results from the preliminary study are related to the overall aim of the descriptive study that is, as stated earlier, to investigate the characteristics of knowledge generated during the service phase of the equipment and how it is reused, in order to identify the main barriers impeding a systematic reuse of knowledge from service and suggest directions for improvement.

#### Types of information

Information about products and processes, together with issues and functions, is widely recognised as relevant in the engineering field. These four types of knowledge have been proposed as the constituents of an ontology for indexing knowledge applicable to a number of different engineering contexts (Ahmed 2005).

In the analysed case study, information about products, in the form of drawings and manuals, was organised in a coherent way and retrievable through well defined interfaces. On the contrary, the other types of information were fragmented in a number of different repositories, depending on the characteristics of the information, the phase of the lifecycle when it arose, the time when it was generated and the project it was related to; this made the available information difficult to retrieve and reuse. The analysis of change documentation showed that, together with standard engineering knowledge, a specific type of process knowledge was relevant for a customised industry: knowledge about *projects* and how they develop over time. In this type of industry, the development of a product is not as grounded upon previous products as in a variant design industry; each project is characterised by a specific history, which includes client's requirements, constraints, working conditions, etc., that motivates the development of a bespoke product. For this reason, information about how a project progresses over time is particularly relevant in a customised industry. However, despite the importance of this type of information, no standard way of handling it was implemented at the collaborating company. This resulted in issues related to the progression of planned work (*carry-over work*) being recurrent across similar rigs.

#### Storing and retrieving information

The analysis of available documentation and the survey on the use of knowledge repositories showed a fragmented picture, where most knowledge repositories were used only at specific phases of the product lifecycle and by a well defined user group. The possibility of sharing information within these small groups resulted in enhancing knowledge transfer within people with common interests, but also posed a barrier to the communication across non-homogeneous groups. Both the effects are well described in literature. The theory of communities of practice explains what characterises a homogeneous group where the exchange of knowledge is motivated by internal drivers (Wenger 2000). Whereas, research on knowledge transfer states that the exchange of knowledge across boundaries, e.g. between non-homogeneous

groups, although difficult to achieve, should be pursued as transferring knowledge across contexts facilitates the identification of untrodden paths and leads to innovative solutions (Carlile 2004).

Additionally, the documentation stored in each repository was associated with a set of indexing criteria that was specific for the repository utilised; hence, it was necessary to adapt the searching method to the repository in use while retrieving information. The survey investigated the number of service engineers and engineering designers using the different search criteria. *Product* and *project* were the most common criteria, used by more than 80% of the participants; consequently these criteria, as a minimum, should be implemented across repositories in order to facilitate the retrieving process. Despite several repositories dedicated to capturing issues, and despite the interest of both service engineers and engineering designers in information about functions, none of the indexing criteria adopted at the collaborating company allowed a search by function or issue, as taxonomies of issues or functions had not been developed at the collaborating company. A similar type of problem also occurred when searching for information by product, as a standard product configuration was not yet implemented at organisational level. Consequently, the indexing criteria applied to some of the repositories highlighted the uniqueness characterising each piece of equipment, whilst in other repositories the selected indexing criteria were more focused upon commonalities between similar pieces of equipment. In order to standardise the way of searching for information by product, it would be necessary to develop a standard set of indexing criteria that consider:

- The different levels of detail at which information about the product could be seen, from system to component levels, developing a suitable taxonomy;
- The levels of commonalities across products as, depending on the circumstances, it might be necessary to retrieve information on a unique piece of equipment installed on a specific rig (e.g. information on its maintenance record) or information on similar equipment installed in various rigs (e.g. to compare the changes implemented);

Finally, the survey showed that both service engineers and engineering designers tended to retrieve information from the same repositories where they were used to storing it, and engineering designers did not widely retrieve information arising from the later phases of the lifecycle when they had not been directly involved in the case. A further reason for the limited retrieval of documentation from service might be linked to its incompleteness. The omission of important information in documentation from service suggests that other informal ways of transferring service cases were adopted at the collaborating company.

#### Reuse of information

The way information was reused and the advantages related to this reuse were not directly investigated in the studies. However, the analysis of change documentation showed that, when a series of rigs shared the same design, the number of changes implemented during the later phases of a rig's lifecycle in order to correct initial design faults significantly decreased from the first rig of the series to the subsequent ones. This suggests that information arising from the lifecycle of the first rig was reused across the rigs of the series. At the same time, the unchanged number of changes related to *carry-over work*, indicates that a better way of transferring process knowledge was still required.

#### *Specificity of the case*

The results regarding the relevance of process knowledge are influenced by the characteristics of the industry taken into account, as the importance of reusing information on how a project was carried out, in order to avoid recurrent issues related to, e.g. planning or installation, is specific to customised industries. On the contrary the results describing the inconsistent and unstructured approach towards information management that emerged from the analysis of the repositories are of general validity, and in agreement with a large body of research in knowledge management (Robertson 2003).

### **4.3 Case study I: Characteristics of knowledge arising from the service phase**

The previous section illustrated the characteristics of the knowledge repositories at the company representing the main case study and investigated how service engineers and engineering designers approached these repositories. This section focuses upon understanding the characteristics of the knowledge generated throughout the later phases of a product's lifecycle and which aspects of this knowledge are of interest to service engineers and engineering designers.

#### **4.3.1 Aims**

The aim of this case study is to investigate the characteristics of the knowledge generated during the later phases of the lifecycle of complex products and to understand what the differences are between the knowledge relevant for service engineers and that relevant for engineering designers. The hypothesis underlying this study, which influenced the development of the initial coding scheme used to analyse the data collected, is that knowledge arising from the service phase can be, like engineering design knowledge, described through a taxonomy based upon four types of knowledge: *product, process, issues and functions* (Ahmed 2005). Hence the study investigated, through a set of interviews with service engineers and engineering designers, whether the taxonomy covered the entire range of knowledge generated during service and which type of knowledge was more important to be made available to service engineers and engineering designers for future reuse.

#### **4.3.2 Methods**

This section illustrates the methods adopted in the case study to collect and analyse the data. A general description of the characteristics, advantages and disadvantages of each of these methods was presented in Chapter 2.

##### ***Interviews with service engineers and engineering designers***

Interviews were carried out at the supplier of drilling equipment, and focused upon the knowledge relevant for service engineers and engineering designers and how this

knowledge was acquired and transferred within and across the phases of the lifecycle of the equipment. A total of 21 interviews with engineering designers and service engineers were carried out at the company headquarters and on a jack-up oil rig during its commissioning phase (see Table 4.8).

Table 4.8 Number of engineering designers and service engineers from the supplier of drilling equipment that have been interviewed.

	<b>Engineering designers</b>		<b>Service engineers</b>	
<b>Location</b>	Headquarters	Rig	Headquarters	Rig
<b>No. of participants</b>	10	2	7	2

All the interviews were semi-structured, the questions asked were related to:

- Characteristics of knowledge from the service phase;
- The mechanisms adopted for acquiring and transferring this knowledge.

All interviews were audio-recorded and lasted between 20-60 minutes, with interviews carried out on the rig shorter due to the limited time available.

The findings from the analysis of the set of interviews with regard to the characteristics of service knowledge are presented in Section 4.3.3; whilst the findings related to mechanisms adopted for acquiring and transferring this knowledge are the focus of Case Study II and described in Section 4.4.3.

### Data analysis

The interviews were transcribed, and divided in 4750 segments, representing meaningful instances. Each segment was coded using a pre-determined coding scheme. One of the interviews was coded also by a second person, Associate Professor Saeema Ahmed-Kristensen, and a coder-reliability test was conducted to compare how the coding scheme was used by different people. The kappa was found to be 0.91; all disagreements were checked and an agreement reached (see Appendix 3 for a description of Cohen's kappa).

The adopted coding scheme was developed from literature on engineering knowledge management and was integrated following a bottom-up approach. The codes selected

were mutually exclusive. A sample of the data collected and how they were analysed using the coding scheme is presented in Appendix 2.

The part of the coding scheme that was developed to investigate the characteristics of the service knowledge followed the taxonomy describing the types of engineering knowledge proposed by Ahmed (2005), and initially included the four codes: *product*, *process*, *issues* and *function*. While analysing the data, more codes were added, following a bottom-up approach, in order to cover the entire range of knowledge described by the interviewees. The final codes used for indexing the types of knowledge were:

- *Product*: including its design and features. Instances describing a product's behaviour in operation were not categorised here but under *operation and lifecycle*.
- *Process and procedures*: related to how to accomplish a task.
- *Changes, issues and improvements*: associated with variations to the original design of the product or to the processes adopted, issues or ideas for improvements.
- *Project*: related to the phases of the development of the drilling equipment, including set up of requirements, reviews of the different phases, interaction with client and suppliers, time schedule, etc.
- *People and organisation*: related to the organisational structure and the awareness of who knows what.
- *Operation and lifecycle*: including knowledge related to the later phases of the lifecycle of a drilling system, e.g. its use, maintenance and service.
- *Function*: representing the task that a particular component or assembly has to fulfil.
- *Domain knowledge* including background technical knowledge on electronics, hydraulics, computer programming, oil industry, drilling methods etc.
- *Others*: if the knowledge described in the interviews could not be described by any of the above categories (e.g. the description was vague).

All the instances could also be coded against two auxiliary codes: 1) *desired condition*, e.g. when an instance regarded a suggestion of the interviewee and 2) *knowledge not available*, e.g. when the interviewee described knowledge that he/she did not have access to. Instances coded against these two auxiliary codes were instances describing hypothetical conditions or negative statements and were treated separately from instances describing the current situation in the analysis.

#### 4.3.3 Results

##### ***Types of knowledge***

The types of knowledge relevant for engineering designers and service engineers respectively were investigated through the interviews and the results are illustrated in Figure 4.9. The results indicate that both groups were interested in *changes, issues and improvements*. Additionally, knowledge particularly relevant for engineering designers was related to *product* (25% of the instances), whilst service engineers were interested in knowledge about *projects* and how these evolved over time.

Examples of instances for each type of knowledge are reported in Appendix 2.



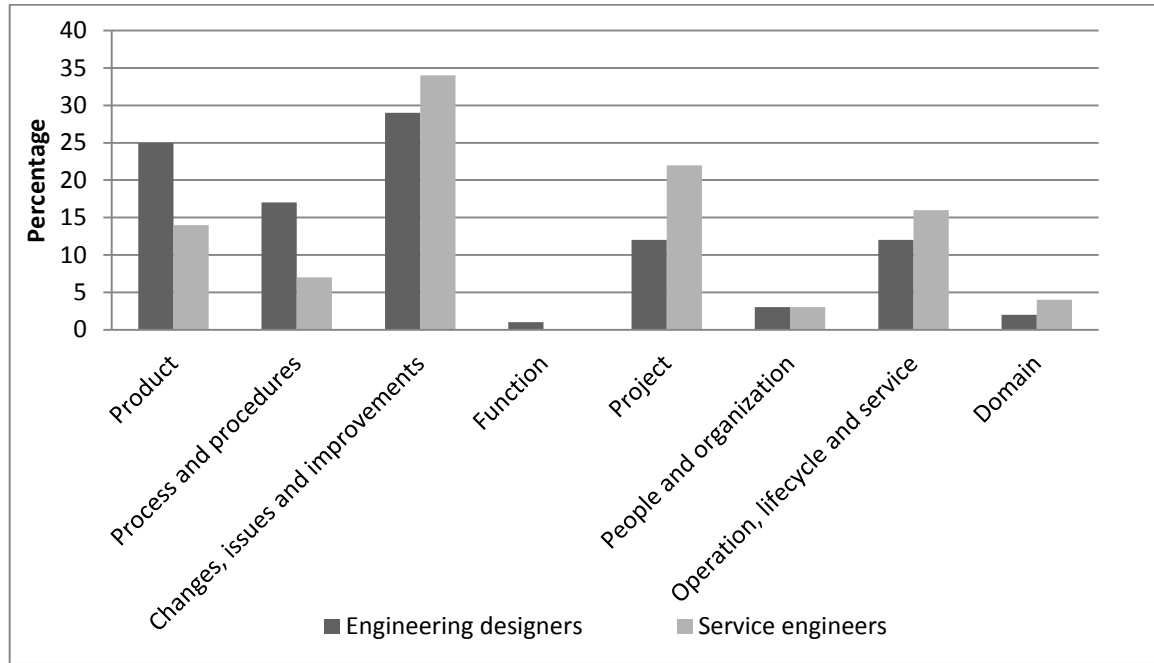


Figure 4.9 Types of knowledge generated during service, as described by engineering designers and service engineers. The values are percentages, calculated on a total of 311 instances for engineering designers and 127 for service engineers.

The interviews also investigated which types of knowledge engineering designers and service engineers would have liked to have access to and which knowledge was described in negative terms, e.g. as not captured in documentation. Instances describing these two conditions were identified using the auxiliary codes *desired condition* or *knowledge not available*. Figure 4.10 and Figure 4.11 illustrate the results. Different trends were observed for service engineers and engineering designers. Service engineers would have desired more knowledge about the *project* to be available, whilst engineering designers perceived *process* knowledge as the type of knowledge they would like to have access to. Differences between the two groups stood out particularly from the analysis of the types of knowledge that were not available. Engineering designers mentioned the lack of available knowledge only once, specifically knowledge about *changes, issues and improvements*, while service engineers mentioned knowledge not available in 45 instances. This perception of knowledge not being available for service engineers was not linked to a particular type of knowledge but included *changes, project, operation, procedures, etc.*

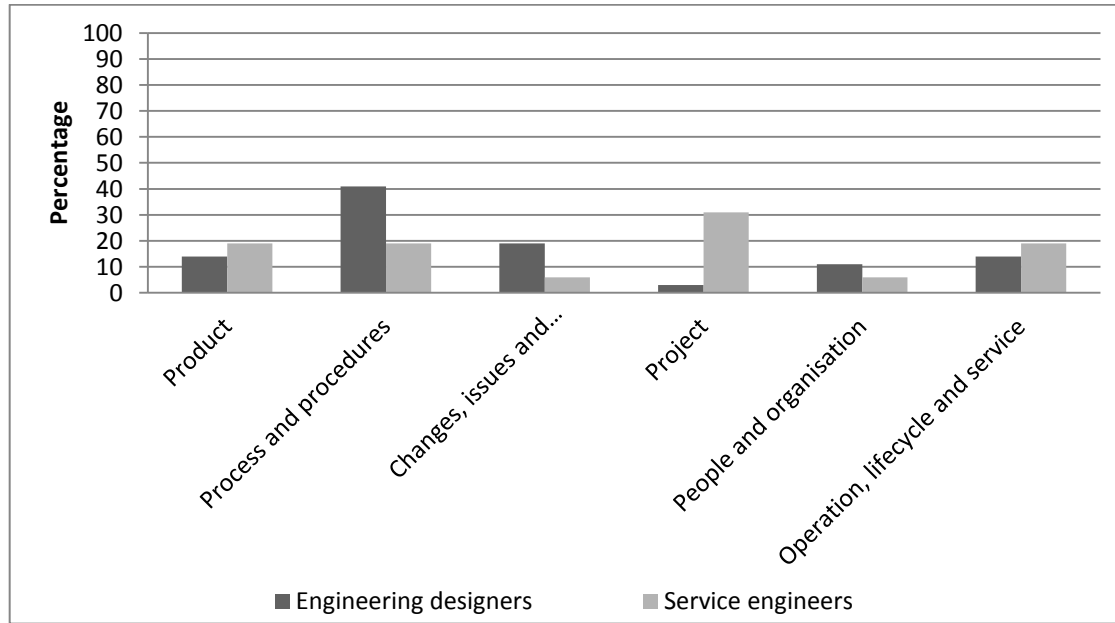


Figure 4.10 Instances describing a desired condition for engineering designers and service engineers, divided by type of knowledge. The values are percentages, calculated on a total of 37 instances for engineering designers and 16 for service engineers.

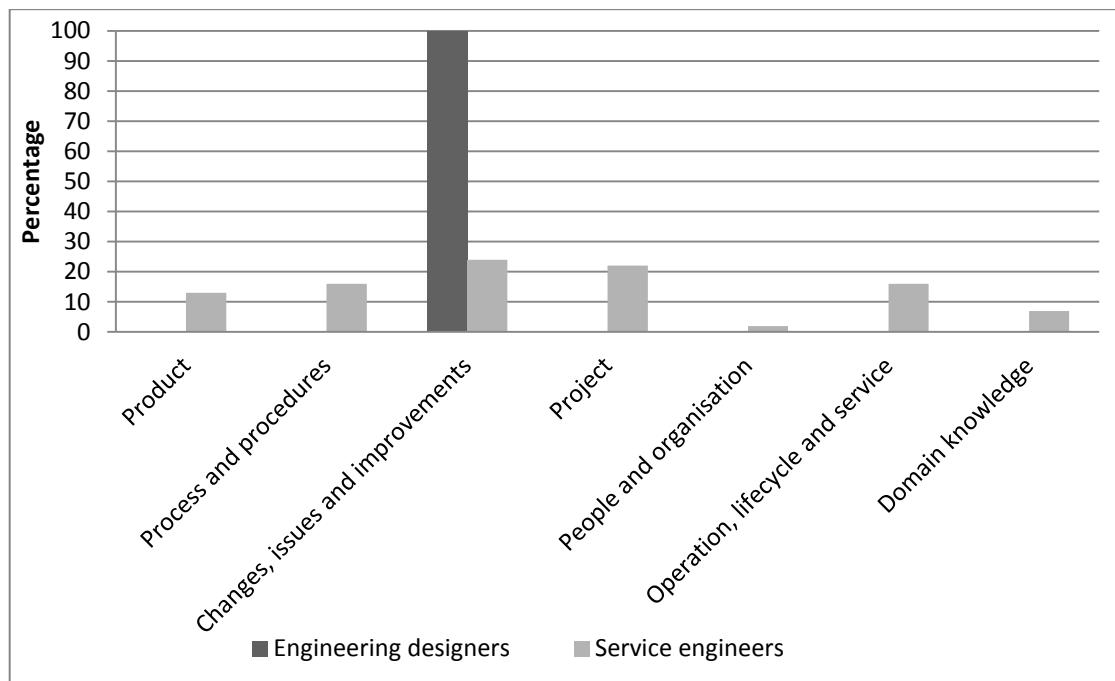


Figure 4.11 Instances describing knowledge not available for engineering designers and service engineers. The values are percentages, calculated on a total of only 1 instance for engineering designers (hence the value is not significant) and 45 instances for service engineers.

### Summary of the findings

The main findings from Case Study I can be summarised as:

- The main type of knowledge generated during service that was of interest for both service engineers and engineering designers was related to *changes, issues and improvements*.
- Engineering designers described only one situation in which relevant knowledge was not available for them; however they suggested that they could benefit from the availability of more knowledge about procedures and standardised processes, e.g. describing how to reuse service knowledge during the development phase.
- Services engineers experienced a lack of knowledge, particularly knowledge about *project*, and described it in 45 instances. They would like to have access to more knowledge about *project* and *changes, issues and improvements*.

#### 4.3.4 Discussion and implications

The results of the analysis of the interviews showed the types of knowledge arising from the later phases of the lifecycle of the equipment, particularly from the service phase, that were relevant for service engineers and engineering designers. Besides the four types of knowledge constituting the ontology proposed by Ahmed (Ahmed 2005), other types were used to code the interviews in order to cover the full range of knowledge characterising the specific case. These included knowledge about the progression of a *project*, the structure of the *organisation*, the *operation and service* of the equipment, and *domain* knowledge. The findings from this case study, i.e. which types of knowledge are more valuable for service engineers and engineering designers, should be taken into consideration when developing a knowledge management strategy aiming to reuse service knowledge, as knowing which knowledge is relevant for service engineers and engineering designers helps develop a strategy that is able to answer their needs and avoids overloading service engineers and engineering designers with irrelevant information.

The paragraphs to follow describe how the different types of knowledge could be effectively reused within the service phase and across phases of the equipment's lifecycle.

#### Knowledge relevant within the service phase

The knowledge generated from the service phase that was found to be relevant for service engineers was about:

- *Changes, issues and improvements* that were related to equipment with characteristics similar to the ones for service.
- *Project knowledge*, describing the history of one rig, in particular the progressing of the works during the installation and commissioning phases.
- *Operation, lifecycle and service* describing the working conditions of a piece of equipment, its maintenance, performances, etc.

When the reuse of knowledge is limited to the service phase, the knowledge transfer process is facilitated by the fact that senders and receivers of the knowledge share the same experiences and the same perspective towards the product; hence, no translation process is required in order to support this transfer. In this context, the transfer of knowledge through codification strategies can take place without the need of including in the documentation a detailed description of the context in which the knowledge was generated, as service engineers share the same type of implicit and tacit knowledge that was acquired during their daily work.

#### Knowledge relevant across phases of the lifecycle

The knowledge generated during the service phase that was also relevant for engineering designers included:

- Knowledge about *changes, issues and improvements* and *product*,
- *Procedures* for developing a product taking into account the reuse of knowledge from past cases.

Hence, knowledge of *changes, issues and improvements* arising during the service phase emerged as of common interest to both service engineers and engineering

designers. Consequently if this knowledge was structured considering the needs of the two groups, it could be used as a boundary object that could facilitate the communication between engineers involved in different phases of the product lifecycle.

When designing a company's knowledge management strategy, the stakeholders and the context in which knowledge is reused need to be defined together with the types of knowledge to reuse in order to ensure that knowledge repositories are structured in an appropriate way. This is particularly evident when knowledge is intended to be reused across projects and across different user groups. In this case the company's knowledge strategy should include a translation process aiming to adapt the information captured into documentation to the needs of the receiver (Carlile 2004).

Specifically, the reuse of service knowledge through a codification strategy should be supported by making information retrievable both at system and at component level. This approach would facilitate both service engineers and engineering designers while retrieving documentation. The interviews confirmed the survey conducted during the preliminary study, which indicated that the two groups viewed the same object from two different perspectives. The engineering designers approached the drilling equipment at the component level and saw it as composed of a number of parts. On the contrary, the service engineers tended to see the drilling system as a whole; when they were assigned to a job they were interested in having an overview of the interactions between the different pieces of equipment and the past history of the rig. This difference in approaches was also visible at organisational level, as the two departments adopted different strategies. The design department was organised by product; each designer specialised in the development of electrical, mechanical or software of a specific piece of equipment under the coordination of the product responsible. In contrast, the service engineers in operation were divided only by their function, as mechanical-hydraulic or electrical, since the priority of the department was to ensure the availability of technicians able to perform a given job at any time;

hence the aim was the creation of a profile of a service engineer with general competences that was able to service the entire range of equipment produced.

### Limitations

The results presented are influenced by the characteristics and the organisational culture of the specific company. For instance, the fact that: (1) the case regarded customised equipment and (2) there was no agreement between the supplier of the drilling equipment and its clients to capture the performances of the equipment and other operational data excluded the availability of a range of service information that other research on the topic has pointed out as of interest for engineering designers (see Chapter 3). The importance of knowledge about current and past projects was also due to the type of product taken into consideration, as when developing a customised product with very strict time constraints it is crucial to efficiently share knowledge among the different stakeholders and reuse effectively the experience acquired from previous projects, e.g. lessons learnt and best practices.

However, the findings from the case study can also be seen to be of general interest, as they are comparable to the findings from other research studies. Research investigating a different industry, namely variant design of complex products (Jagtap, Aymer et al. 2007), also stressed the importance of reusing knowledge related to failures, maintenance and lifecycle.

## **4.4 Case study II: Knowledge transfer within and across organisational boundaries**

Case Study I, presented in Section 4.3, defined the characteristics of service knowledge and identified the types of knowledge that are more relevant for service engineers and engineering designers respectively. Case Study II, presented in this section, provides an analysis of how the knowledge from service is transferred within and across lifecycle's phases.

#### 4.4.1 Aims

Case study II aimed to understand the mechanisms adopted to transfer knowledge within the service phase and across phases of the lifecycle, and to analyse the knowledge transfer in different contexts by taking into consideration the perspectives of the different stakeholders that play a role in the knowledge transfer process.

The oil industry, which represented the context of the two studies presented in this section, is characterised by high mobility of technical personnel, service engineers and drilling operators in particular, frequently travelling or changing position. Hence a systematic transfer of operational experience was expected to be supported by the implementation of knowledge management strategies based upon codification.

#### 4.4.2 Methods

Two studies were investigated through interviews with multiple stakeholders:

- 1) At the supplier of drilling equipment already taken into consideration in the previous sections, interviews were carried out with service engineers and engineering designers;
- 2) At the drilling contractor that owned some of the rigs where the drilling equipment in question was installed, interviews were carried out with project managers and operators of the drilling equipment.

The first study focused upon the knowledge transfer mechanisms within service and across phases of the product's lifecycle, and was based upon a set of interviews investigating how knowledge was acquired and transferred.

The second study focused upon the series of four oil rigs, which was already taken into consideration in relation to change notifications in Section 4.2.3, to investigate the knowledge transfer from the perspective of the drilling contractor owning and operating the rigs. Interviews were carried out on board the first rig of the series to investigate the expected knowledge transfer mechanisms and on board the second rig in order to investigate the actual situation.

A total of 21 interviews with engineering designers and service engineers from the supplier of drilling equipment and 18 interviews with project managers and rig operators from the drilling contractor were carried out, as shown in Tables 4.9 and 4.10. The participants from the supplier of drilling equipment were the same as those interviewed for Case Study I, as each interview covered both the topics.

Table 4.9 Number of engineering designers and service engineers working at the supplier of drilling equipment that have been interviewed.

	<i>Engineering designers</i>		<i>Service engineers</i>	
<b>Location</b>	Headquarters	Rig	Headquarters	Rig
<b>Number of participants</b>	10	2	7	2

Table 4.10 Number of project managers and rig operators working at the drilling contractor that have been interviewed.

	<i>Project managers</i>		<i>Rig operators</i>	
<b>Location</b>	Rig 1	Rig2	Rig 1	Rig2
<b>Number of Participants</b>	4	4	4	6

All the interviews were semi-structured, the questions asked were related to the mechanisms adopted while acquiring and transferring knowledge. The interviews were audio-recorded and lasted between 20-60 minutes, with interviews carried out on the rigs shorter due to the limited time available. The results from the two sets of interviews are illustrated in Section 4.4.3.

#### Data analysis

The interviews were transcribed and coded using a pre-determined coding scheme, following the same method adopted in Case Study I.



Table 4.11 Coding scheme.

Categories	Codes (subcodes)	Definition	Literature
<b>Knowledge transfer</b>	Sender/receiver	Parties involved in knowledge transfer	Lin <i>et al.</i> (2005)
	Initiation mechanisms (push, pull, symmetric)	Transfer pulled by the receiver, pushed by the sender, or occurring due to a dialogue between the parties involved (symmetric)	McMahon <i>et al.</i> (2004)
	Type of capture (personal, codified)	Transfer in codified ways or relying on people	Hansen <i>et al.</i> (1999), McMahon <i>et al.</i> (2004)
	Dimensions (within a rig, across rigs, across projects)	The context relevant to transfer knowledge	Bottom-up approach
<b>Auxiliary code</b>	Knowledge not available, desired situation.	This code identifies when an instance describes knowledge in negative terms (e.g. not available), and separates instances describing the existing situation from those where an ideal situation is described	Bottom-up approach

The coding scheme was developed from literature on knowledge management and organisational learning, and was completed following a bottom-up approach. The scheme included different categories, each one embracing codes and subcodes. The subcodes within any of the codes are mutually exclusive. An overview of the categories and the main codes is shown in Table 4.11. A sample of the collected data and of how they were analysed using the coding scheme is presented in Appendix 2.

As shown in Table 4.11, the interviews were analysed in respect to knowledge transferred according to a *sender-receiver* framework, distinguishing between *personalisation* and *codification* as manners for capturing and transferring knowledge, and distinguishing between *push*, *pull* and *symmetric* as initiation mechanisms.

The initial coding scheme was applied iteratively and completed with the three dimensions of knowledge transfer that have been elicited from the interviews (see Figure 4.12):

- *Within a rig*: transfer of knowledge related to the progress of a rig, its lifecycle and operation (e.g. through handover, records, talk among colleagues).
- *Across rigs*: reuse of knowledge from the first rig into the next ones of the same series (e.g. through moving the crews from one rig to another, transfer of change records, reuse of procedures).
- *Across projects*: knowledge gathered through lessons learnt, personal experience, maintenance records and reused in subsequent projects (i.e. a different series of rigs).

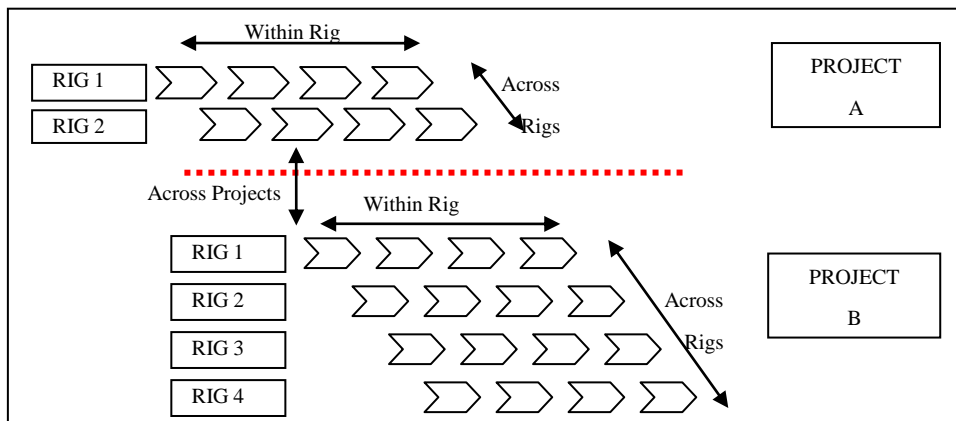


Figure 4.12 Transfer within rig, across rigs and across projects

The identification of the dimension in which knowledge is transferred was relevant for the study, as how knowledge is reused is expected to influence how it should be captured and retrieved.

The three dimensions described here were integrated into the predetermined coding scheme and taken into consideration during the analysis of the interviews.

Additionally, as in the previous case study, all the instances could also be coded against two auxiliary codes: 1) *desired condition*, e.g. when an instance regards a suggestion of the interviewee and 2) *knowledge not available*, e.g. when the interviewee described knowledge that he/she did not have access to. In the analysis of the interviews these types of instances were separated from statements describing the current situation.

The interviews from the supplier of drilling equipment were analysed in respect to the knowledge transferred within the service phase and across phases of the lifecycle of the equipment, while interviews with project managers and operators from the drilling contractor were specifically analysed from the point of view of the knowledge transferred within and across projects.

The patterns that emerged from a quantitative analysis of the results from the coding scheme were further investigated through a qualitative analysis of relevant instances in order to obtain further insights on the mechanisms used for transferring knowledge. The results are reported in the section to follow.

#### 4.4.3 Results

##### ***Knowledge transfer within service and across departments***

The case study conducted at the supplier of drilling equipment investigated how knowledge was transferred within and across phases of the equipment lifecycle. The results are presented below.

##### Strategies for capturing and transferring knowledge

The first analysis of the interviews from the supplier of drilling equipment regarded how knowledge was captured: distinguishing between knowledge captured into repositories, hence transferred through *codification* strategies, and knowledge internal to the individuals, and consequently transferred through *personalisation* strategies such as informal communication among colleagues or meetings. While knowledge transferred through *personalisation* always results in new knowledge available for the receiver, when *codification* strategies are adopted, the process could result in knowledge captured into documentation, but not necessarily reused.

The adoption of personalisation or codification strategies for capturing and transferring knowledge was investigated in relation to the types of knowledge described in Section 4.3 and the two groups participating in the interviews, namely service engineers and engineering designers. The results, summarised in Table 4.12, show that the fraction of instances describing *personalisation* and *codification*

strategies was comparable for the two groups, with approximately 60% of the knowledge captured in documentation. The distribution of the number of instances describing the strategy used by service engineers and engineering designers when transferring a specific type of knowledge was also comparable. The only types of knowledge for which the prevailing of strategy for knowledge transfer differed between the two groups were *domain knowledge* and knowledge about *people and organisation*. However, the low number of instances describing these types of knowledge (less than 3) made this divergence not significant.

Table 4.12 Percentages of instances describing knowledge captured through personalisation and codification strategies. The percentages refer to the number of instances of engineers and engineering designers respectively describing each type of knowledge.

	<i>Service engineers</i>		<i>Engineering designers</i>	
	<i>Codification</i>	<i>Personalisation</i>	<i>Codification</i>	<i>Personalisation</i>
Changes, issues and improvements	52	48	63	37
Domain knowledge	0	100	50	50
Operation, lifecycle and service	72	28	76	24
People and organisation	100	0	67	33
Process and procedures	80	20	74	26
Product	46	54	41	59
Project	77	23	57	43
Total	60	40	59	41

A comparison between Table 4.12 and Figure 4.9 in Section 4.4.3 suggests that the types of knowledge whose transfer still heavily relied upon *personalisation* strategies, i.e. *product* and *changes, issues and improvements*, were also the types of knowledge that were most relevant for both service engineers and engineering designers.

The mechanisms adopted for transferring knowledge are further investigated in the sections to follow, where commonalities and differences between the transfer of knowledge within service and the transfer taking place across phases of the lifecycle are described.

### Transfer mechanisms within and across phases

Table 4.13 shows the results of the analysis of knowledge transfer between service engineers and engineering designers in relation to a *sender-receiver* framework and the initiation mechanisms: *push* (when the sender makes knowledge available without a specific request for it), *pull* (when the receiver actively searches for knowledge) or *symmetric transfer* (when both the sender and the receiver play an active role in the transfer process: e.g. in meetings). The transfer within the design phase tended to be *symmetric*, occurring through meetings or personal contacts, whilst transfer across phases and within service was mainly asymmetric: *pushed* when transfer occurred from service to design or within service, *pulled* from design to service. Service engineers tended to actively make knowledge available by *pushing* it towards other service engineers and engineering designers, whilst, at the same time, they needed to pull knowledge from engineering designers. As shown in Table 4.13, 44% of knowledge received by designers was pushed from service. However this knowledge was mostly transferred through codification by storing documentation into the company's repositories and was not necessarily reused by the engineering designers.

Table 4.13 Knowledge transfer between service engineers and engineering designers and its mechanisms; the values are percentages of the total number of instances describing respectively engineering designers and service engineering as receivers.

Sender	Receiver	
	Engineering designers % (72 instances)	Service engineers % (36 instances)
<b>Engineering designers</b>	<b>24</b>	<b>47</b>
Push	4	19
Pull	3	25
Symmetric	17	3
<b>Service engineers</b>	<b>76</b>	<b>53</b>
Push	44	25
Pull	21	11
Symmetric	12	16
<b>Total</b>	<b>100</b>	<b>100</b>

One of the engineering designers that was interviewed used the following words to describe the way he accessed knowledge from the service phase:

*I cover the position of department manager and use my people working with the technical stuff. If I need someone competent for a piece of equipment, the product responsible is the best man because every report is back to him. If there is some problem if they use the CCN, the mail or something it will go through him as he is the specialist on the equipment.*

This tendency of relying on engineering designers covering senior positions (i.e. the product responsables) for accessing information about a *product* as well as *changes, issues and improvements* led to overloading experienced designers with new tasks. In addition to completing their own tasks, they were asked to support other positions by providing their personal knowledge, as described by Jensen et al. (Jensen and Ahmed-Kristensen 2009).

Also service engineers heavily relied on personalisation strategies while collecting or transferring knowledge from service. For instance, a service engineer described how he used to deal with knowledge about *issues* arising during service, in the following terms:

*That varies, it is not done in a systematic way. It depends, sometimes just a telephone call or whatever if you really know exactly who is dealing with it. But sometimes you just don't bother, if it isn't important. When we are fixing things in our end of the company we of course go back to the product.*

Statements like the ones reported above stressed the importance of the role played by product responsables to support the transfer of knowledge at the collaborating company.

From a qualitative analysis of the interviews it emerged that senior positions, both among engineering designers (i.e. product responsible) and service engineers (i.e. senior service engineers), acted as knowledge brokers, facilitating the transfer of personal and codified knowledge. A knowledge broker is described in literature as an

intermediary who facilitates the knowledge transfer process providing links, pointing to sources or directly supplying knowledge (Hargadon 1998); brokering practices include crossing organisational boundaries, translating and interpreting available knowledge according to the needs of the receiver and supporting the transfer of knowledge across units in the organisation (Pawlowski and Robey 2004). In the case study analysed, the interviewees, when in need of information not generated by their own department, tended to contact a broker from another department rather than to search for available documentation. This resulted in the broker supplying information in the form of e.g. personal communication, ad-hoc reports created to satisfy the receiver needs or already available documentation.

When knowledge was transferred through codification strategies, the knowledge repositories played a central role in the communication flow, together with the sender and the receiver (see Figure 4.13), as the sender pushes information into repositories, and then the same information can be pulled by the receiver or pushed to him in the form of notification, alert etc. In this context the knowledge broker could support the transfer process by pointing to available documentation from the repositories or requesting further information from the sender.

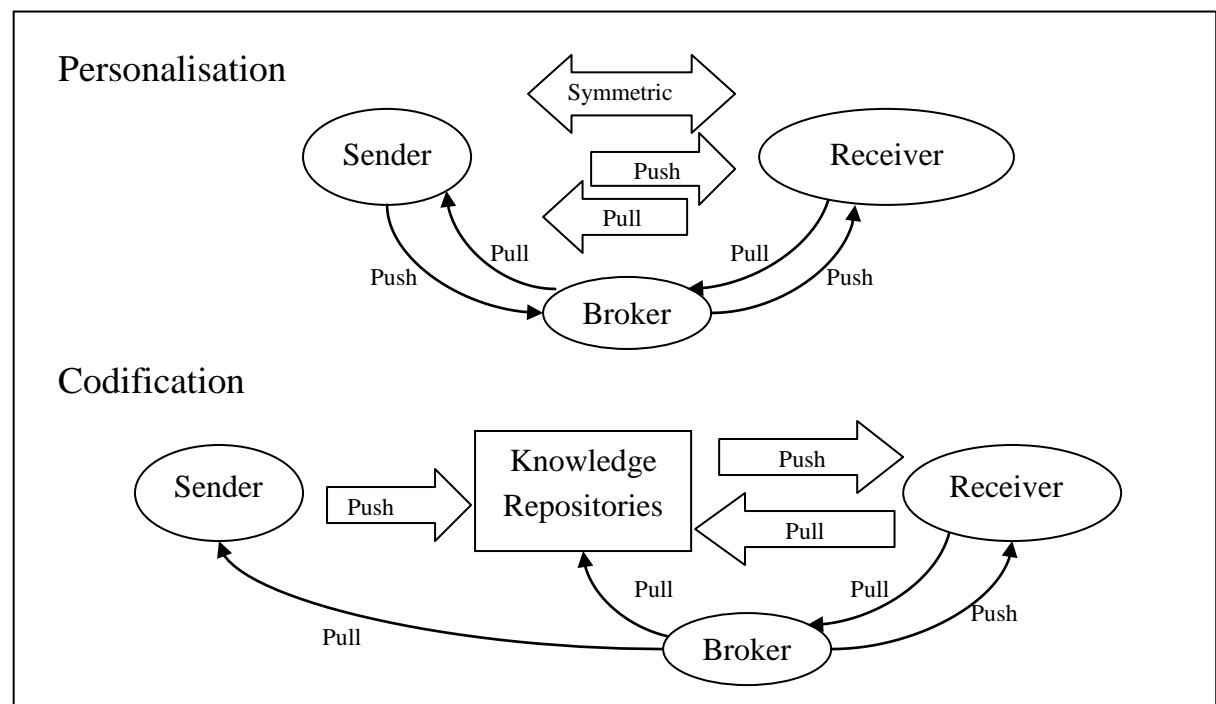


Figure 4.13 Knowledge transfer through personalisation and codification strategies.

### Knowledge transfer within service

The mechanisms characterising knowledge transfer among service engineers were investigated in relation to the types of knowledge that were transferred and the strategy adopted. As shown in Table 4.14, knowledge transferred through codification strategies was primarily pushed into repositories in the form of documentation about *changes, issues and improvements*. However, none of the service engineers interviewed actively retrieved (i.e. *pulled*) this type of documentation from the repositories: whilst they retrieved documentation about a *project* and the *operation* of the equipment, they used to access information about *changes* through personalisation strategies.

Table 4.14 Types of knowledge transferred within service and initiation mechanisms. The values are percentages calculated against the number of instances describing knowledge transferred through codification and personalisation strategies respectively.

	<b><i>Codified (43 instances)</i></b>	<b><i>Personal (24 instances)</i></b>
<b>Push</b>	63	25
Changes, issues and improvements	33	21
Operation, lifecycle and service	12	4
Process and procedures	5	0
Product	2	0
Project	12	0
<b>Pull</b>	21	42
Changes, issues and improvements	0	13
Domain knowledge	0	4
Operation, lifecycle and service	9	0
Product	2	13
Project	9	13
<b>Symmetric transfer</b>	16	33
Changes, issues and improvements	0	21
Operation, lifecycle and service	5	4
Product	5	0
Domain knowledge	0	4
Project	6	0
Process and procedures	0	4
<b>Total</b>	100	100

A similar pattern emerged from the analysis of the mechanisms for symmetric transfer of knowledge, e.g. which occur during meetings at fixed stages of a project. The



documentation generated in this context was focused on the progressions of a *project*, the development of a *product* or reports from fixed gates of the *lifecycle*. However, it did not include systematic reviews of *changes, issues and improvements*, and this type of knowledge was transferred through personal communication among service engineers.

These results suggest a mismatch between the information about changes that was captured in repositories and what was needed by service engineers. Service engineers relied on *personalisation* strategies when they wanted to access this type of knowledge, despite the fact that information on *changes* was extensively captured in documentation (33% of the instances describing knowledge captured in documentation regarded *changes*),

#### Knowledge transfer from service to design

Finally the knowledge transfer from service to design was specifically analysed in relation to its content and the initiation mode; the results are illustrated in Table 4.15. The main codified knowledge that was transferred across organisational boundaries was about *changes, issues and improvements*. This was mostly *pushed* by service engineers, as it represented more than 50% of total instances describing transfer of codified knowledge, and to a lesser extent *pulled* by engineering designers. Personalised knowledge was equally pushed and pulled from operation to design. Knowledge *pushed* to engineering designers by service engineers mainly concerned *changes*, whereas engineering designers were also pulling knowledge about *operation* and, to a lesser extent, *project* and *product*. From this analysis, *changes, issues and improvements* arising during service emerged as the main knowledge transferred to engineering designers, confirming the results from the investigation of the types of knowledge relevant for the two groups described in Section 4.4. However, it is evident that no one strategy for transferring this type of knowledge was followed, as transfer occurred both through codification and personalisation.

The interviews also suggested that knowledge transfer between service engineers and engineering designers was a relevant issue from the perspective of service engineers,

who experienced recurrent problems and would have liked to have been involved in the design process in order to ensure that the experience from the field was taken into account while designing new products. On the contrary, a systematic transfer of knowledge from the service phase was less relevant from the perspective of engineering designers, who did not perceive a systematic reuse of inputs from service while designing a product as their main priority. Moreover, they expected service engineers to make them aware of issues arising during service by being the drivers of the knowledge flow, as expressed through the words of a designer:

*I think the operation division is the driver because they have the contact from the customer; they are sitting close to the customer.*

This explains why most of the information was *pushed* from service to design.

Table 4.15 Types of knowledge transferred from service to design and initiation mechanisms. The values are percentages calculated against the number of instances describing knowledge transferred through codification and personalisation strategies respectively.

	<b>Receiver: engineering designers</b>	
<b>Sender: service engineers</b>	<b>Codified % (23 instances)</b>	<b>Personal % (27 instances)</b>
<b>Push</b>	<b>70</b>	<b>41</b>
Changes, issues and improvements	52	37
Project	9	4
People and organisation	4	0
Operation, lifecycle and service	4	0
<b>Pull</b>	<b>22</b>	<b>37</b>
Product	0	4
Changes, issues and improvements	13	15
Project	0	7
Operation, lifecycle and service	9	11
<b>Fixed</b>	<b>9</b>	<b>7</b>
Changes, issues and improvements	0	4
Operation, lifecycle and service	9	4
<b>Personal contact</b>	<b>0</b>	<b>15</b>
Product	0	4
Changes, issues and improvements	0	11
<b>Total</b>	<b>100</b>	<b>100</b>

The limited interest of the designers for knowledge arising throughout the lifecycle of a product may be linked to the characteristics of the oil industry, which is very

conservative and still sees the provision of service and maintenance as a source of profit for the supplier of drilling equipment. Hence there was not a strong motivation for focusing upon product lifecycle issues, which is the case when product-service systems are supplied, e.g. in the aerospace industry.

These results highlighted issues connected with the suitability of knowledge repositories for transferring knowledge across departments: although service engineers made service information available in a codified manner, designers tended to retrieve information from service through personalisation, as stated by an engineering designer during an interview.

*During project phases, you start to know people, you get in contact with people, so you are after some years in the company, you are definitely able to ask the questions to the right people, if you want to. So it is actually easier for us to be able to ask people.*

Additionally, in agreement with Argote's framework for knowledge transfer (Argote et al. 2003), the interviews also described knowledge transfer occurring by moving knowledge reservoirs. Moving personnel across departments had been the focus of an employee's development project implemented by the company before the interviews were carried out. The project, although successful, was interrupted due the exponential development of the oil business that impeded the temporary allocation of engineering designers to other departments. An engineering designer described that experience using the words below.

*Some of our designers were hospitalizing in operation division, as part of the senior service staff. So, two of my guys, stayed here for 1 year each, and were actually handling questions coming in from service, and that was very useful when it came to getting experience from live operating machinery into the design phase. But that ended when all went sky-high, so we needed that experience within the design technical department, so the project was pulled back. Up until then, that was very useful for us, and I believe it was very useful also for operation department.*

Nonetheless, the benefits of that program were still visible at the company as designers who participated in the program had a better vision of the lifecycle of the equipment and had formed a network of contacts in the operation department which remained active.

Despite the rotation program being no longer active at the time of the interviews, temporarily moving personnel, particularly software developers, from the design department to service was still common to support the most critical parts of the commissioning phase, and had the positive effect of facilitating the communication across departments.

### Summary of the findings

The main findings that emerged from the analysis of the knowledge transfer are summarised as follows.

- On average 60% of instances describing the types of knowledge were about knowledge captured into documentation, however knowledge about *product* and *changes, issues and improvements* (that Section 4.3 indicated as the most important types of knowledge that needed to be reused) was still mostly accessed through personalisation.
- Service engineers were the main drivers of knowledge transfer, by making knowledge available both through personalisation and through codification strategies.
- Senior positions acted as knowledge brokers, helping the receiver access relevant knowledge.
- Despite documentation about *change, issues and improvements* being available, this type of knowledge was primarily assessed through personalisation strategies, both by service engineers and engineering designers.

### ***Knowledge transfer within and across projects***

This section describes the results from the analysis of the interviews with project managers and drilling operators from the drilling contractor, who owned the series of four rigs whose characteristics were anticipated in Section 4.5.2. Two sets of interviews were conducted at the end of the commissioning phase of the first and the second rig of the series respectively and investigated whether the strategy for transferring knowledge that was described from the interviews on the first rig was confirmed during the set of interviews on the second rig.

#### **Types of knowledge**

The types of knowledge mentioned during the interviews were analysed in relation to the dimensions of knowledge transfer for which they were relevant, see Table 4.16. The principal type of knowledge transferred in any dimension was related to *project* (including lessons learnt, comments from the crew and the client, status, outstandings, project documentation and experience) followed by knowledge on *changes, issues and improvements*.

Table 4.16 Types of knowledge against the dimensions of knowledge transfer (R1= Rig1; R2= Rig2). The values are percentages calculated against the total number of instances

	<b>Across rigs</b>		<b>Within rig</b>		<b>Across projects</b>		<b>Others</b>		<b>Total</b>	
	R1	R1	R 2	R2	R1	R2	R1	R2	R1	R2
Product	2	2	2	1	2	2	0	0	6	5
Changes and issues	18	2	4	16	2	0	0	4	24	22
Project	11	2	9	21	6	5	1	14	27	42
Organisation	0	0	0	1	0	0	0	0	0	1
Operation and service	2	9	1	9	1	2	1	0	5	20
Process and procedures	0	0	2	2	0	1	0	0	2	3
Others	30	6	1	1	4	0	1	0	36	7
Total	63	21	19	51	15	10	3	18	100	100

The project managers from the drilling contractor who were interviewed on the first rig of the series expressed the intention of reusing the experience from that rig, particularly experience related to the problems that had occurred, while constructing and operating the subsequent rigs, as expressed in statements such as the following:

*I think that the problems we have detected on this rig are not going to happen in the second rig, it's just because I know that the project manager will be very focused on those things at the next rig so that they don't face the same problems.*

A total of 36% of instances from the interviews on the first rig that described the reuse of knowledge did not directly refer to any specific type of knowledge. This trend was particularly evident in the case of knowledge transferred across rigs, as almost 50% of the instances describing the transfer in this dimension did not refer to any specific type of knowledge and addressed knowledge in general terms e.g. as experience or lessons learnt. On the contrary, interviews from the second rig indicated that the knowledge transferred across rigs was mostly related to *project, changes and issues*, and *operational experience*. Additionally, the investigation of the knowledge actually transferred, that was carried out through the interviews on the second rig, showed that these types of knowledge were not specifically addressed to any one dimension, e.g. knowledge of *project* might have been used both within a rig and across rigs, or *changes* leading to improvements might have been implemented both in other rigs of the same series and in other projects. This resulted in difficulties in reusing available information as the structure and content of documents did not reflect the multiple ways in which knowledge could have been reused.

The analysis of the data from Table 4.16 with respect to the three dimensions of knowledge transfer, indicates that the majority of instances described transfer occurring *within a rig* and *across rigs* part of the same series, with instances of transfer *across projects* (from one series of rigs to another) being less than 20% of the total. However, as the questions asked during the interviews primarily investigated the

transfer *across rigs*, the higher number of these instances reflected the nature of the questions asked.

Table 4.16 also shows the discrepancy between the data from the two sets of interviews with regard to the undefined context of knowledge transfer. Instances coded against *others* described knowledge that could be used in different dimensions, e.g. both within a rig and across rigs. From the second rig of the series it emerged that 18% of instances described knowledge without identifying the dimension in which this knowledge was relevant. This suggests that, while the expected situation was well defined, in the actual situation the context in which knowledge was to be reused was not clearly identified.

#### Initiation mechanisms and transfer strategies

The motivation for knowledge transfer was analysed by investigating the initiation mechanisms, specifically whether knowledge was *pulled*, that is driven by a request for information from the receiver that actively searches for it, or *pushed*, when the sender makes knowledge available before a specific need for it has arisen. A third transfer mechanism was also identified: *symmetric transfer* due to, for instance, meetings or standard reports. In symmetric transfer there is no specific need or request for knowledge and both the sender and the receiver play an active role in the transfer process. Similar trends were seen in both sets of interviews. Table 4.17 shows that less than 15% of the total instances describing the transfer of knowledge were due to symmetric transfer. In both the rigs, about a quarter of the instances on knowledge transfer described knowledge *pulled* by the receiver, whilst the majority of cases (50%) were cases of *pushing* knowledge, where the sender made knowledge available without the receiver actively requesting this knowledge. The examples of symmetric knowledge transfer were mostly related to planned meetings, e.g. to discuss the status of the project within the current rig, or to the analysis of lessons learnt that may be relevant to the next three rigs. Further mechanisms that initiated knowledge transfer (indexed against *other*) were related to moving personnel across rigs.

Table 4.17 Initiation mechanisms (R1= Rig 1; R2= Rig 2).

Knowledge transfer	<i>Push</i>		<i>Pull</i>		<i>Symmetric</i>		<i>Other</i>		<i>Total</i>	
	R1	R2	R1	R2	R1	R2	R1	R2	R1	R2
Number of instances	31	58	18	25	7	15	6	15	62	113
Percentage	50	51	29	22	11	13	10	13	100	100

To better understand the knowledge transfer process the analysis of the initiation mechanisms needs to be supported by the analysis of the strategies adopted to transfer knowledge: *codification* and *personalisation*. *Pushing* knowledge emerged to be the main initiation mechanism and occurred through *codified* channels; however, this strategy does not ensure that the information is reused at the receiver side. On the contrary, the knowledge that is *pulled*, i.e. requested or actively sought, identifies that there is a need for this knowledge and it is of interest for the receiver.

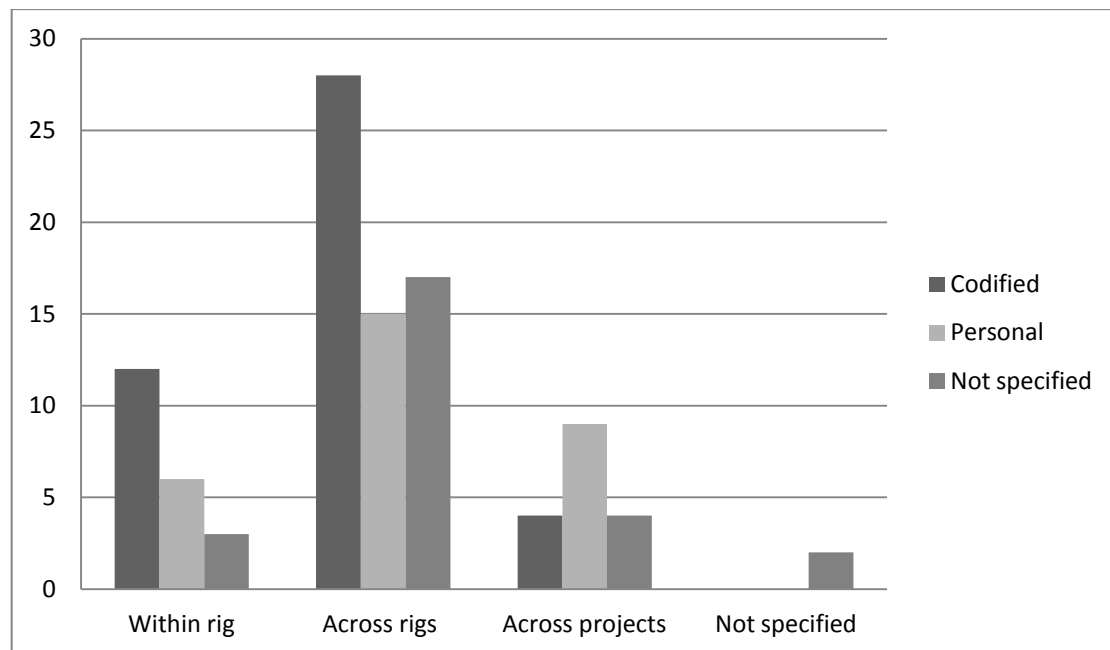


Figure 4.14 Knowledge transfer strategies, from the interviews on the first rig (in percentages).

From the interviews on the first rig (see Figure 4.14), 26% of instances describing transfer of knowledge in the three dimensions did not specify the strategy that should be adopted (*Not specified* column in Figure 4.14); this was particularly evident for



instances describing the transfer of knowledge across similar rigs. Additionally, the first set of interviews indicated that knowledge was expected to be transferred across rigs through *codification* (Figure 4.14) whilst data from the second rig showed the prevalence of *personalisation* (Figure 4.15). In more detail, the interviews on the first rig indicated that *codification* was expected to support knowledge transfer *within rig and across rigs*, whilst *personalisation* strategies were more likely to facilitate the transfer of experience *across projects*. However, the picture drawn from the second rig was different (see Figure 4.15); *codification* supported transfer *across projects* and was not particularly utilised within a rig's lifecycle. As the interviews primarily investigated the transfer *across rigs*, the higher number of these instances reflected the nature of questions asked; hence the distribution of the number of instances on knowledge transfer across the three dimensions does not provide any insight.

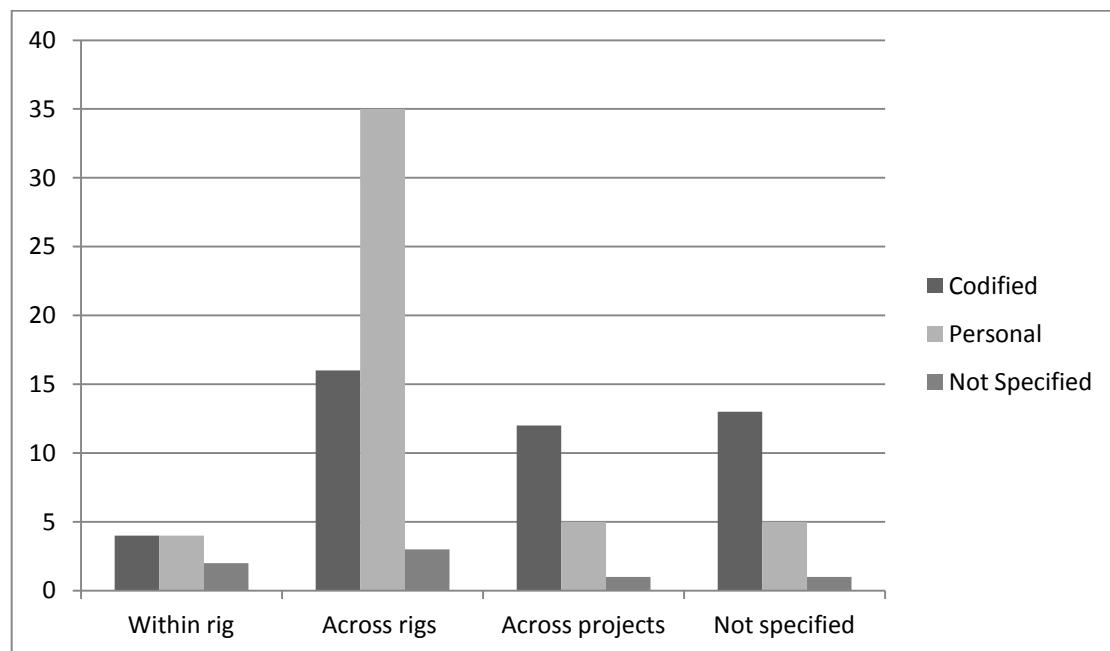


Figure 4.15 Knowledge transfer strategies from the interviews on the second rig (percentages)

From a comparison of the instances describing knowledge transfer from the first and the second rig, differences emerged in relation to (1) the dimensions (*within rig, across rigs, across projects*) in which the transfer took place and (2) the strategy adopted. The picture that emerged from the first set of interviews was quite defined with respect to the dimension, i.e. *across rigs*, in which the knowledge should be

reused, whilst the strategy was not clear. Moving from the expected to the actual situation, on the one hand the strategies that needed to be adopted became more delineated; on the other hand, the context in which the knowledge was to be transferred became more confused as this could be relevant for different dimensions. The characteristics of the knowledge transferred in the different dimensions have been investigated in more detail through a qualitative analysis of the related instances; the results are described below.

### **Knowledge transfer within a rig**

Both sets of interviews showed similar results with regards to the types of knowledge transferred within a rig, whilst the methods to transfer knowledge were somehow different. In particular, training on the equipment through simulation was important on the first rig; however it was less relevant in the subsequent rigs of the series, as the knowledge of the drilling system was facilitated by drilling operators with experience from the first rig later assigned to the other rigs. The methods adopted for transferring knowledge were influenced by the experience of the individuals. Novice and trainees tended to rely upon IT systems and the company procedures, while more experienced personnel tended to follow less formal and more proactive ways of transferring knowledge, for example by following the progresses of a rig before they started being actively involved in it.

### **Knowledge transfer across rigs (part of the same series)**

The mechanisms adopted to transfer knowledge across rigs, which were part of the same project, were influenced by the phase of the lifecycle in which the transfer occurred. These are described below.

*Design phase:* this phase was common for all the rigs of the series and completed by a single design team that approached the four rigs as part of the same project. Design solutions were transferred from one rig to the next without changes.

*Installation and commissioning:* this phase took place at the same shipyard for all the four rigs with a six month delay between the rigs, hence facilitating the exchange of

knowledge due to physical proximity and the transfer of crews across rigs. During the installation phase knowledge was transferred across rigs through different channels, i.e.:

- Support teams were based at the yard to coordinate the transfer of experience across rigs and facilitate the handover from design to operation;
- Personal contact occurred between different crews due to the proximity of the rigs;
- Crews were moved across rigs to provide support in critical phases;
- Documentation on issues arising during installation and commissioning was transferred from the first rig to the next;
- ‘Lessons learnt’ programs were set up: 1) internally after 90 days of operation and 2) externally with third parties at a later date;
- Workshops were organised to transfer start up problems to the other rigs;
- Comments from the crew and the client were captured, evaluated by project management and transferred across rigs if considered relevant.

The two sets of interviews showed differences between the expected transfer mechanisms and the actual ones. Particularly knowledge transfer was expected to take place through lessons learnt meetings and moving the personnel involved in the commissioning of the first rig to the second rig once the commissioning was completed. These initiatives did not occur as expected due to delays in the completion of the first rig. On the contrary, knowledge transfer occurred through personalisation thanks to the physical proximity of the rigs that facilitated informal communication between crews, and through temporarily allocating the crew assigned to the second rig on the first one in order to provide support at critical stages.

During installation and commissioning, time and cost constraints limited the implementation of improvements and the transfer of the solutions across rigs. This resulted in rig personnel being sceptical towards planned procedures for transferring knowledge across rigs and preferring to postpone interventions that did not involve safety issues to the operation phase.

*Operation:* the rigs operated in different areas, resulting in a reduction of the knowledge transfer across the rigs, particularly through personalisation. The characteristics of the transfer of knowledge in this phase are described below.

- Operational experience was gained by the drilling crew of the second rig by visiting the first rig while in operation;
- Communication across rigs was based on personal initiative;
- No systematic transfer of operational knowledge occurred across rigs or to engineering designers;
- No transfer of operational procedures was observed. Although the drilling systems were identical, personnel from the second rig preferred to write their own procedures rather than reuse those from the first rig.

The distinction between the different phases was mirrored in the knowledge transfer program organised by the company, as separate lessons learnt meetings were set up at the end of each phase until the end of the warranty period. When knowledge transfer across rigs occurred, it took place among people involved in the same phase of the lifecycle and usually covering the same role in different rigs. No initiatives aimed to capture the knowledge arising throughout the lifecycle once the warranty period was concluded.

### **Knowledge transfer across projects**

The transfer of knowledge across projects occurred in two directions, each of these is discussed below:

- Capture of knowledge with the purpose of reusing it in future projects;
- Reuse of experience from past projects.

As the design was transferred across the four rigs without any changes, excluding the correction of faults compromising safety on board, the knowledge emerging from the lessons learnt meetings was expected to be reused in future projects. Despite that, no effort was made to structure this knowledge in a way to facilitate its retrieval and reuse in the future.

The knowledge that was reused from past projects during the development of the analysed series of rigs was personal experience, particularly of members of the design

and the project management teams. Experience of the operators was not used during the design of the rigs. As a result, issues regarding reliability, maintenance and operation were common to current and previous rigs. Hence, as also emerged from the analysis of the transfer of knowledge across rigs, transfer was more likely to occur through personalisation mechanisms and to be confined to people involved in the same phase of the lifecycle.

Table 4.18 Knowledge transfer in the different dimensions in relation to the phase of the lifecycle and the knowledge object

	<i>Within rig</i>	<i>Across rigs</i>	<i>Across projects</i>
Design	(Not investigated)	<b>Personal:</b> Same design and project management teams ( <i>project, issues</i> )  <b>Codified:</b> Transfer of design solutions ( <i>project, issues</i> )	<b>Personal:</b> Design and project managers with long history within the company ( <i>project</i> )  <b>Codified:</b> Lessons learnt and project documentation from previous projects ( <i>project</i> )
Installation and commissioning	<b>Personal:</b> Personal communication, following construction ( <i>project, issues, product</i> )  <b>Codified:</b> Status reports, crew comments, punch list, updated drawings, handover procedures ( <i>project, issues, product</i> )	<b>Personal:</b> Knowledge of other rigs captured at the yard. ( <i>issues, project, product</i> )  <b>Codified:</b> Reports from lessons learnt meetings, crew comments, testing procedures ( <i>project, issues, procedures</i> )	<b>Personal:</b> Personal experience and communication ( <i>projects, product</i> )  <b>Codified:</b> Commissioning procedures, certificates ( <i>product, procedures</i> )
Operation	<b>Personal:</b> Training on new machines, presence of operators during yard stay ( <i>project, product</i> )  <b>Codified:</b> Training, workshops, procedures, manuals ( <i>procedures, product</i> )	<b>Personal:</b> Experience and communication ( <i>product, issues, operation</i> )  <b>Codified:</b> Record of comments from the crew ( <i>issues</i> )	<b>Personal:</b> Personal experience and communication ( <i>product, operation</i> )  <b>Codified:</b> Safety alerts ( <i>issues</i> )

### Summary of the findings

Table 4.18 summarises the main findings and couples each phase of a rig's lifecycle and each dimension of knowledge transfer with the relevant types of knowledge. Differences emerged between the knowledge that was significant during operation and the knowledge that was relevant during design and commissioning. After a rig enters into operation, project knowledge was no longer relevant while knowledge about past operational processes was more relevant for reuse, particularly to create operational procedures to share within the series of rigs. The analysis of the knowledge transfer mechanisms in the series of four oil rigs also showed differences between the expected and the actual situation with regard to:

- Types of knowledge: the initial knowledge management strategy did not explicitly refer to any specific type of knowledge while the interviews from the second rigs showed that the knowledge that was transferred across rigs was mostly related to: *project* and *changes and issues*.
- Mechanisms: despite the willingness of the management to transfer knowledge through codification strategies, the preferred strategy was personalisation.
- Dimensions: knowledge, particularly about *changes and improvements*, was expected to be transferred across rigs, however barriers related to time and costs impeded this from happening.

#### 4.4.4 Discussion and implications

The two case studies carried out in order to investigate the knowledge transfer mechanisms that were adopted throughout the lifecycle of drilling equipment considered both the supplier of the equipment, developing and servicing it, and the drilling contractor that defined the requirements provided to the supplier, coordinated the commissioning of the rig and its equipment, and operated the drilling equipment once it was installed on the oil rig.

The approach of the two parties towards the drilling equipment was different: the supplier of the drilling equipment had a deep knowledge of the product, as it was

responsible for its design, but a limited knowledge from the later phases of its lifecycle since, after the installation and commissioning phase, it was only involved in servicing the equipment upon the contractor's request. The drilling contractor, on the contrary, had extensive knowledge from the operational phase but only general knowledge of the design of the equipment.

However, despite the differences between the two companies, the characteristics of the processes for transferring knowledge that emerged from the studies were similar. The main type of knowledge that was transferred was, in both cases, about *changes, issues and improvements*; and, although codified strategies for capturing and transferring this type of knowledge had been implemented, knowledge transfer primarily occurred through *personalisation*.

The results from the interviews carried out with different stakeholders did not confirm the initial hypothesis that a systematic transfer of service knowledge was taking place, supported by *codification* strategies. Personalisation strategies were still extensively used to gather information despite knowledge management strategies based on codification being developed at organisational level and prescribed to capture available knowledge into documentation. This tendency was exemplified by the fact that knowledge, particularly regarding *changes, issues and improvements* was pushed into the company's repositories by the sender, yet rarely pulled by the receiver; when this occurred the receiver tended to be supported by a knowledge broker pointing to relevant information.

The reasons for this limited use of available documents as a source of information include:

- Capturing and storing: the information captured was incomplete, scattered across repositories and not always relevant for the receiver, additionally the indexing criteria adopted did not match the receiver's way of searching for information.
- Retrieving: difficulties in reusing experience were related to the need to evaluate similarities across cases in order to understand whether information

from a past case is relevant in a new context. This explains the need of a broker acting as facilitator to transfer codified knowledge, particularly across departments.

Although the knowledge management strategies were specific for the companies taken into consideration, the findings are in line with other research that described the difficulties for engineering designers to retrieve information from knowledge repositories and identified colleagues as the most frequent source of information (Marsh 1997), with nearly 80% of information requests answered from memory.

#### **4.5 Summary**

The findings from the analysis of the case studies within the oil industry are consistent with what is described in literature for more general cases and summarised in Chapter 3. The case studies analysed showed the lack of a systematic reuse of knowledge from service, despite the willingness of the management to support experience transfer both within and across departments.

Various reasons explain this mismatch between expectations of the management and practice. For instance:

- The knowledge management strategies focused on capturing and storing information into repositories but did not take into consideration how it should be accessed and reused, e.g. by identifying whether knowledge from service should be taken into account when designing the next generation of products or during the service phase.
- A variety of repositories for similar purposes, frequently modified, was available for storing information. The choice of where to store information was dependent on the phase of the lifecycle when information was generated, the department involved, etc.
- There was a gap between the information stored and the information needed, particularly when information was relevant across organisational borders, as



documents were generated without taking into consideration who would be interested in reusing them.

These issues confirmed Robertson's analysis of common knowledge management issues in industry (Robertson 2003). Additionally, the gap between the information stored and the information needed confirms the common issue of poor identification of the main objective while designing a knowledge management system to support knowledge reuse, as highlighted by Storey (Storey, Barnett 2000).

Despite the similarities across research projects from different areas, the issues related to the organisation of repositories are even more critical when dealing with knowledge arising throughout the lifecycle of complex products, as in this context, given the length of the timeframe when knowledge is generated:

- A knowledge management strategy based on personalisation is not an option;
- Different stakeholders are involved throughout the product's lifecycle;
- The purpose for capturing knowledge might change over time.

The main issues related to the reuse of service knowledge that emerged from the case studies are summarised below and will be the foundation of the model for managing service knowledge proposed in Section 5.

The paragraphs below provide a summary of the main findings from the case studies that constituted the descriptive study presented in this chapter.

### Knowledge management strategy

The strategies adopted for transferring knowledge were not coherent, as knowledge transfer mechanisms were not defined at organisational level and were dependent on the specific situation. When transfer occurred within the service phase, knowledge was transferred through a mix of codified and personal approaches; whereas the transfer of knowledge across the different phases of the lifecycle occurred mainly through personal approaches and due to the support of senior employees, acting as knowledge brokers.

The combination of personal and codified approaches towards knowledge transfer that characterised the service practice was not consistent with the willingness of the

management to base the internal transfer of knowledge upon codification strategies. This preference for codification strategies was motivated by the long product lifecycle, and the high turnover and internal mobility of the employees, that made strategies based upon personalisation hazardous. The knowledge management strategies based upon codification that were implemented at the companies that were taken into consideration were not effectively used to transfer service knowledge. On the contrary, service knowledge was generally transferred due to the initiative of the individuals through personal approaches.

The lack of a systematic reuse of knowledge from service, which can be achieved only through codification strategies, resulted in:

- Changes motivated by faults correction being detected late in the product lifecycle, as there was no standard communication path across departments.
- Recurrent issues being addressed in different ways.
- Support of senior positions being required in order to supervise service interventions and validate the selected solution through personal experience.
- Service engineers being used to informing engineering designers of problems arising from service through personalisation strategies, also in the cases when documentation is available.

## Repositories

The knowledge management tools adopted to capture knowledge were frequently changed and often relevant only for a restricted user group (e.g. department) or during a limited phase of the product lifecycle. Information was fragmented across repositories depending on the context in which it was generated. Additionally employees did not extensively retrieve information from repositories due to e.g. incompleteness of available information, lack of training on how to use available documentation and restricted access to the repositories. The result was that repositories were often perceived as black boxes, necessary to store information that was only rarely retrieved.

### Gap between information available and users' needs

The collaborating companies captured into documentation a wide range of knowledge generated during service; the types of knowledge considered more relevant to be reused both within service and across phases of the product's lifecycle were *changes, issues and improvements* and *product*.

The documentation was often created and stored in the repositories without considering how it should be reused. This was more evident when knowledge was expected to be reused across departments and lifecycle phases. Engineering designers generally approached *products* at the component level, while service engineers were interested in how systems worked and the interaction between pieces of equipment, this difference in approaches towards the same product influenced the type of documents created by the two groups and the search criteria implemented in the repositories when the documents were stored. Consequently the documents created by one group were not relevant for the other one.

Knowledge about *changes, issues and improvements*, although relevant for both service engineers and engineering designers and extensively captured into documentation, was accessed mainly through personalisation approaches, as available documentation was not able to answer the needs of the two groups.

### Findings in relation to the research questions

The findings from the descriptive study answer to the first research questions, as identified in knowledge about *changes, issues and improvements* and about *products* the types of knowledge generated during service that are most relevant for service engineers and engineering designers. The case studies also indicated that, despite the implementation of knowledge management strategies for transferring information based on codification, knowledge transfer still heavily relied on personalisation.

The following chapter analyses the reasons that made the knowledge management strategies ineffective and develops a model that aims to facilitate the reuse of knowledge from service.

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## 5. Prescriptive study: a model for reusing service knowledge

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### 5.1 Introduction

This chapter describes the prescriptive study that was based upon the analysis of the case studies presented in Chapter 5.

Section 5.2 summarises the main findings from the case studies, with particular evidence on issues that needed to be addressed in order to improve the reuse of service knowledge. Section 5.3 compares these issues with common issues described in literature and already anticipated in Chapter 3; this section also presents two knowledge management frameworks, proposed by Earl and Kamara respectively. Chapter 5.4 proposes a model for reusing knowledge specifically addressed to engineering knowledge generated during service; this model was developed following the framework proposed by Kamara. Finally, Section 5.5 integrates Kamara's framework with elements that emerged from the case studies and were not explicitly addressed by the original framework.

### 5.2 Findings from case studies

#### Knowledge to capture

The results of the analysis of the case studies showed the types of knowledge arising from the later phases of the lifecycle of the equipment, particularly from the service phase, that were relevant for service engineers and engineering designers. These included knowledge about the progression of a *project*, the structure of the *organisation*, the *operation and service* of the equipment, together with *domain* knowledge that characterises the engineering field. It is important to be aware of these types of knowledge while developing a knowledge management strategy to reuse service knowledge, as implementing a strategy that does not target specific types of knowledge and does not answer the needs of expected users would result in a waste of time and resources.

### Knowledge relevant within the service phase

The main types of knowledge emerging from the service phase that were found to be relevant for service engineers regarded:

- *Changes, issues and improvements*, related to equipment with characteristics similar to the ones for service.
- *Project knowledge*, describing the history of a rig, in particular the progression of the works during the installation and commissioning phases.
- *Operation, lifecycle and service* describing the working conditions of a piece of equipment, its maintenance, performances, etc.

When the reuse of knowledge is circumscribed within the service phase, the transfer process is facilitated by the fact that the service engineers generating knowledge and the ones reusing it share the same background and perspective towards the knowledge object; hence, no translation process is required in order to support this transfer. When knowledge from a service case is captured into documentation, the need of describing the context in which this knowledge was generated in order to facilitate its reuse is not as great as when knowledge is expected to be transferred across organisational boundaries, as the service engineers share the same implicit and tacit knowledge acquired during their daily work.

### Knowledge relevant across phases of the lifecycle

The knowledge related to the service phase that was also relevant for engineering designers included:

- Knowledge about *changes, issues and improvements*;
- Knowledge about *product*,
- *Procedures* for developing a product taking into account the reuse of knowledge from past cases.

Hence, knowledge of *changes, issues and improvements* arising during the service phase emerged as of common interest to service engineers and engineering designers. If this knowledge was structured considering the needs of the two groups, it could be used as a boundary object able to facilitate communication between the engineers

involved in different phases of the product lifecycle. However the different perspectives of the two groups were reflected in the nature of documentation. Service documentation aimed to capture dynamic knowledge valuable mainly at the moment when it was issued and available in the form of service reports or status descriptions. In contrast, design documentation represented static knowledge entailed in drawings, valid throughout the lifecycle of a product and relatively easy to reuse across projects. The comparison of the findings from the case studies to the types of service knowledge relevant for engineering designers in other industries, namely variant design of complex product (Jagtap, Johnson et al. 2007), highlights that knowledge on failures, maintenance and lifecycle is relevant for both variant and customised industries whilst the importance of project and procedural knowledge was only seen in the case of customised equipment.

#### Knowledge transfer

The analysis of the case studies indicated that the strategies adopted for transferring knowledge were not coherent, as knowledge transfer mechanisms were not defined at organisational level and were dependent on the specific situation. Within the service phase, knowledge was transferred through a mix of codified and personal approaches; whereas the transfer of knowledge between departments involved in different phases of the product's lifecycle occurred mainly through personal approaches and the support of senior employees, who acted as knowledge brokers. Although information was pushed by service engineers into repositories accessible to engineering designers, it was rarely reused. This result confirms other research studies stating the difficulties in transferring information when sender and receiver do not have a shared understanding of a topic (Zack 1999).

The combination of personal and codified approaches towards knowledge transfer that characterised the service practice was not consistent with the willingness of the management to base the internal transfer of knowledge upon codification strategies. This preference for codification strategies was motivated by the long lifecycle of the



equipment and the high turnover and internal mobility of the employees, which made strategies based on personalisation hazardous.

The interviews identified various reasons that explained this mismatch between expectations of the management and practice, including:

- The main collaborating company implemented several knowledge management tools without defining how available information needs to be reused.
- Both service engineers and engineering designers perceived a gap between the information that was available from the repositories and the information they needed. This gap was particularly evident for information that could be relevant across organisational borders (e.g. across divisions or business unit).

The findings from the analysis of the case studies are consistent with those described in literature for more general cases. For instance, the issues that Robertson identified as the main barriers for the success of a knowledge management strategy in industry included (Robertson 2003):

- An inconsistent and unstructured approach to knowledge management;
- A lack of knowledge sharing between related business units;
- An over reliance on long-service members of staff as sources of knowledge.

Additionally, the gap between the information stored and the information needed confirms the common issue of poor identification of the main objective of a knowledge management system that was highlighted by Storey and Barnett (2000).

### **5.3 Knowledge management frameworks from literature**

When knowledge management research follows a prescriptive approach, it results in the development of:

- Sets of factors to take into account while managing knowledge;
- Frameworks defining the steps to follow when developing a knowledge management strategy.

Various frameworks have been proposed in literature in order to support the definition of a knowledge management strategy. A common element across frameworks is the identification of a specific problem that needed to be addressed, as several case studies showed that when a standard knowledge management solution is adopted without defining a clear objective and being adapted to the specific context where it is implemented, its adoption does not lead to the expected positive effects (Storey, Barnett 2000).

Figures 5.1 and 5.2 illustrate the frameworks proposed by Earl (2001) and Kamara et al. (2002) respectively. The first is a general framework that addresses the conceptual phase and is useful to define how knowledge management could be used to solve the identified problem (performance gap).

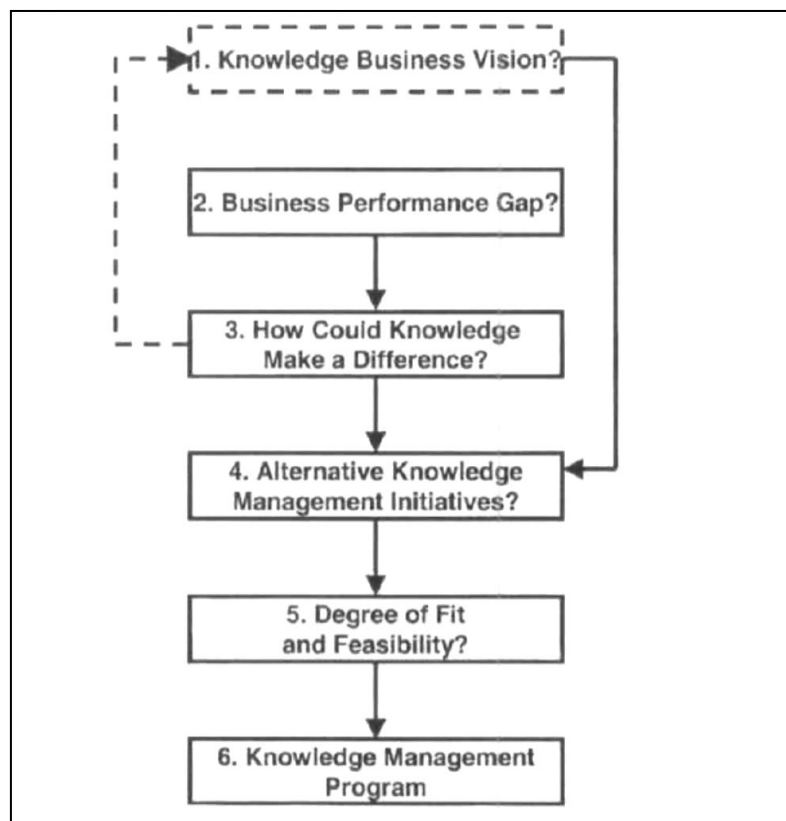


Figure 5.1 Earl's Framework for developing a knowledge management strategy.

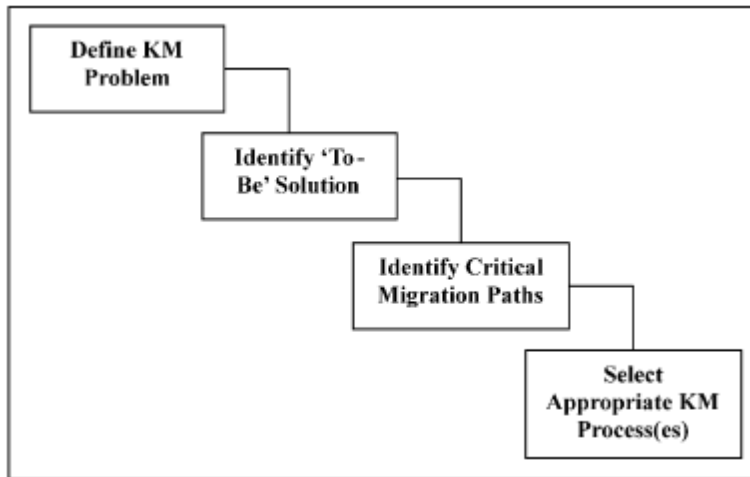


Figure 5.2 Kamara's framework for knowledge transfer.

The second framework suggests the steps to follow from the identification of the problem to the definition of the knowledge management processes to be implemented. This framework will be followed in Section 5.4 to develop a knowledge management model that supports the reuse knowledge generated during the service phase of a product.

#### **5.4 Definition of a knowledge management strategy for reusing service knowledge**

In this section the findings from the case studies described in Chapter 4 are applied to the framework proposed by Kamara in order to define a knowledge management model for managing service knowledge.

The analysis of the knowledge transfer practices at the supplier of drilling equipment was in line with general research in the knowledge management field and suggested factors that needed to be systematically taken into consideration when developing a knowledge management strategy aiming to support knowledge transfer through codification. However, the long timeframe when knowledge was generated and the variety of stakeholders involved in the process of knowledge creation made issues related to the implementation of codified strategies for transferring knowledge more critical than in other cases described in literature.

The four steps for developing a knowledge management model that constitute to Kamara's framework (see Figure 5.2) have been applied to the context of the supplier of drilling equipment, the results are described in the following sections.

#### 5.4.1 Step 1. Problem identification

The first step of the framework is aimed at identifying the problems to tackle.

The analysis of the case of the supplier of drilling equipment showed that knowledge management strategies based upon codification were available in order to systematically capture knowledge arising throughout the different phases of the lifecycle of drilling equipment; however the preferred way to transfer knowledge across members of the organisation was still based upon personal approaches. Additionally, despite knowledge about *changes, issues and improvements* from service being relevant for both service engineers and engineering designers, no specific strategy was developed in order to facilitate the reuse of this type of knowledge.

The consequences of the lack of knowledge management strategy supporting a systematic reuse of information from service included:

- Recurrent issues were not addressed in a consistent way as experience from past cases was not systematically reused during a service intervention.
- Support of senior positions was required in order to supervise service interventions and validate the selected solution through personal experience.
- Service engineers informed engineering designers of problems arising from service through personalisation strategies even when documentation was available, as engineering designers did not search for relevant information from the available documentation.

Various areas of improvement, related to the phase of the lifecycle where knowledge was expected to be reused, emerged from the analysis of the case studies. In the service phase, knowledge supporting service engineers while servicing the drilling equipment was not easily available from the repositories in a form that could be reused in new cases, particularly:

- Documentation from previous cases was difficult to reuse during a new service intervention when the person responsible for the intervention had not been involved in the past case. Documentation was not structured and reflected the point of view of the service engineer generating it. Consequently, obtaining relevant information from available documentation was not always possible and similarities across cases were hard to assess as reports were not created for their reuse.
- It was difficult to obtain an overview of a project over time; to understand what was done and what works were still incomplete, etc.

During the design phase, engineering designers incorporated experience from service into the design of new products through their personal knowledge, and they expected service engineers to inform them (e.g. the relevant product responsible) in case of major problems. They rarely referred to documentation, as going through the available documentation was time consuming, with challenges related to:

- Relevance of the information;
- Reliability, as validation of the likely cause of failure was often missing;
- Completeness;
- Fragmentation, as information about a service case was often scattered across repositories.

#### 5.4.2 Step 2. Definition of the to-be state

The second step of the framework consists of the definition of the to-be state. The case studies indicated that the main type of knowledge, whose reuse should be facilitated both within the service phase and across phases of the equipment lifecycle, is knowledge about *changes, issues and improvements*. Due to the characteristics of the oil industry, such as high internal mobility and turnover of employees, the preferable way of transferring knowledge is through documentation.

A systematic reuse of this type of knowledge is beneficial in two dimensions:

- During the service phase;

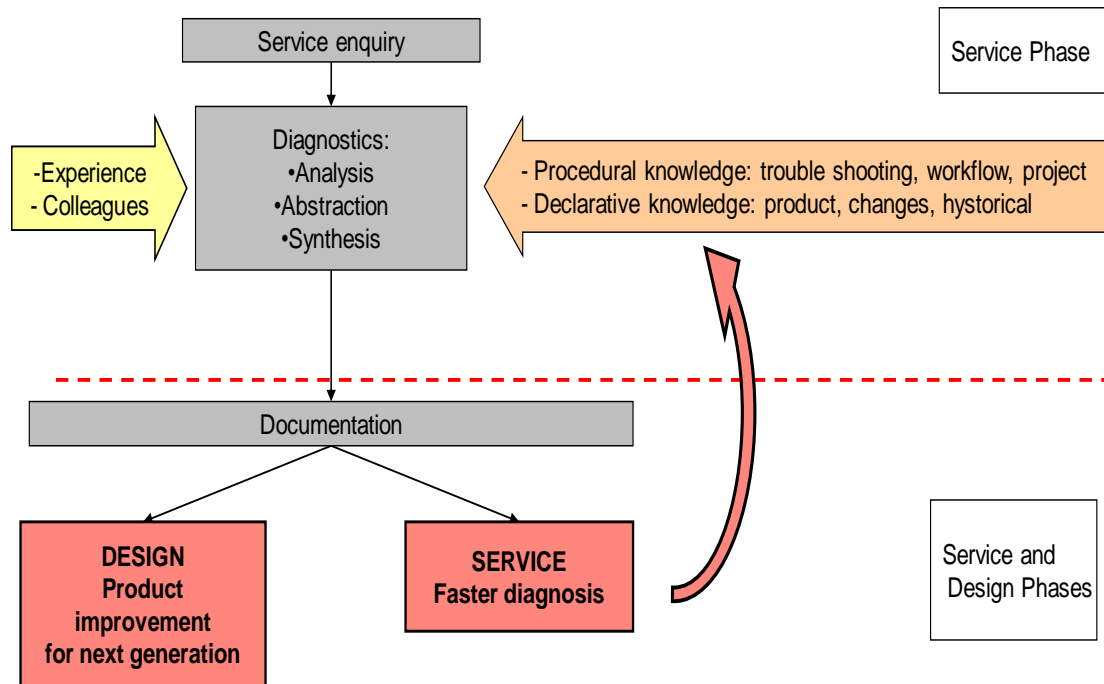


Figure 5.3 To-be state for knowledge reuse.

- During the development phase.

The to-be state is summarised in Figure 5.3. The two dimensions for reusing service knowledge are discussed in the following paragraphs.

### **Reuse within service: faster diagnosis**

In the case studies considered, a service case was initiated, either internally or externally, by a service enquiry expressing a perceived gap between expected and actual conditions (e.g. failure, performances, reliability, usability). The case was analysed by service engineers and the solution was defined in agreement with the client both on technical and on financial aspects. This process relied upon the personal experience of the service engineers. The use of documentation from past cases occurred mainly when service engineers had been directly involved in those cases or when senior service engineers acted as knowledge brokers and pointed to relevant documentation.

The to-be state allows supporting service interventions by systematically accessing and reusing documentation that provides:

- Information from similar cases;
- Information of the design of the product (e.g. drawings, requirements)
- Historical information on the lifecycle of the product or component involved (e.g. previous failures, changes).

The aim for the reuse is to adopt a trouble-shooting process that is consistent across cases and allows reusing already adopted solutions when predefined similarity criteria are met.

Reusing service knowledge within service helps provide faster and more consistent service interventions through the reuse of:

- Procedural knowledge: giving consistency to trouble-shooting process and project management in general.
- Declarative knowledge: providing service engineers with solutions implemented in previous similar cases.

### **Reuse in the design phase: product improvement**

The reuse of service knowledge during product development helps improve the design of the next generation of products, by avoiding issues already detected in previous products and evaluating suggestions for improvement.

The equipment taken into account in the selected case studies was designed based upon the client's requirements. During the development process engineering designers used their own personal experience and were supported by the design of similar equipment developed for previous projects. Experience from the service phase was reused in the form of personal knowledge of the engineering designers or when changes implemented during service were captured in the product documentation (e.g. drawings). The analysis of how the equipment already developed behaved during service was not reviewed in the formal workflow. The to-be state includes a systematic reuse of information from service while developing new products in order to reduce the number of changes arising from the later phases of the product's lifecycle, enhance the product's performances and facilitate the continuous improvement of the product. The systematic reuse of knowledge from service is facilitated through:

- Capturing service knowledge into documentation according to the needs of engineering designers (e.g. standardising it, making it accessible at component level and available through a single interface);
- Including a review of documentation from previous projects (with respect to *issues, changes, improvements* together with maintenance data, product performances etc.) as a phase of the development process.

#### **5.4.3 Step 3. Identification of migration paths**

Once the objectives of the knowledge management strategy are defined, the paths to follow to meet these objectives need to be delineated. The following suggestions are made to enable relevant information from service to be identified quickly and eventually reused:



- Indexing documentation of a service case against the product and component it refers to, in order to allow engineering designers to access information at component level;
- Structuring the documentation of a service case by:
  - Problem description
  - Trouble-shooting
  - Root cause
  - Solution.

The case studies identified information overload as a major barrier to reusing available documentation, confirming previous research (Wallace, Ahmed et al. 2005). Retrieving and reviewing each document from past service interventions that could be relevant for an open case is a time consuming activity and does not always bring the desired result. The personal experience of the receiver is important to assess similarity between cases and understand how information from a past case could be reused. This issue is addressed by various research fields, including Case-Based Reasoning. Research on Case-Based Reasoning suggests a four step process (see Figure 5.4) in order to facilitate learning from past cases. The four steps are: retrieve, reuse, revise and retain.

The last two steps are particularly important for their consequences on a knowledge management strategy, as they indicate how to capture and store knowledge arising from a new case by integrating it into existing documentation, which is revised and retained in the form of new knowledge. This concept is taken into account in the migration paths illustrated in Figure 5.5, where an “analysis” step precedes the retrieval and reuse of documentation. The analysis step leads to the distinction between processed documentation (after analysis) and non-processed documentation (before analysis), which are described in more detail here.

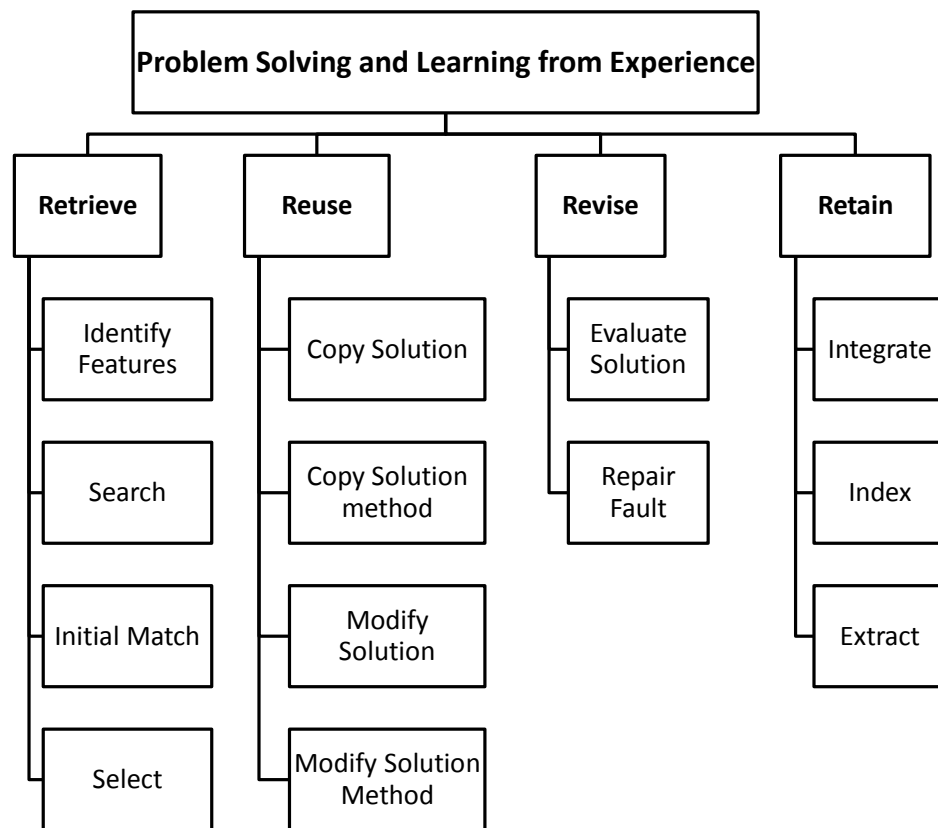


Figure 5.4 The four steps that support learning from past cases according to Case-Based Reasoning (Aamondt and Plaza 1994).

Non-processed information: includes all the documents that have been generated in relation to a case in order to answer specific needs, e.g. service-requests, spare part orders, service reports, repair methods. This type of information is strictly related to the specific case, the moment in time when it has been generated and the context it refers to. Those users without prior awareness of the nature of the case and its context have difficulties in:

- Searching for relevant documentation;
- Obtaining a sufficient overview of the context of the original case, that allows the comparison of cases and the assessment of their relevance;
- Extracting the information needed from this type of documentation.

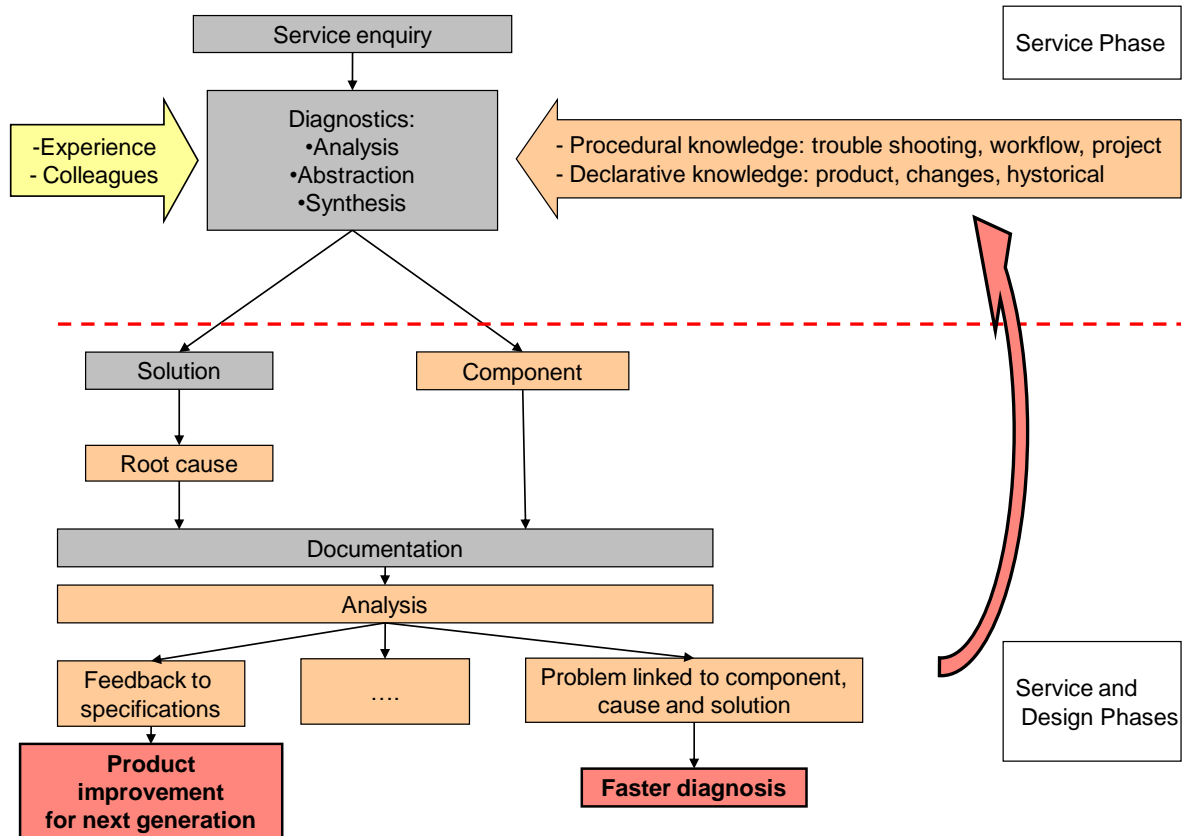


Figure 5.5 Migration paths: the RSK (Reuse of Service Knowledge) model proposed based on the findings from the descriptive studies.

Processed information: refers to information that is the result of the analysis of documents or practices. This type of information is easier to transfer to new cases as:

- The context of its reuse (e.g. type and severity of damages to which a solution could be applied) is described;
- It is explicitly generated to be reused across cases; hence it includes only relevant information;
- It represents a trustworthy source;
- The number of documents is limited compared to those capturing non-processed information.

Given the advantages in reusing processed information a company should aim to gather documentation from similar cases and analyse it in order to generate a set of standard documents, which are easier to retrieve and reuse in new cases than unprocessed information.

The scheme of the migration paths illustrated in Figure 5.5, will be referred to in the rest of the thesis as the model for Reusing Service Knowledge (RSK model); it represents a general model that can be applied beyond the specific case as the type of knowledge it is targeted to, changes and issues from service, has been proved to be relevant for the engineering domain by a number of studies. Furthermore, the path proposed to support knowledge reuse is validated by research on Case-Based Reasoning.

#### **5.4.4 Step 4. Selection of knowledge management processes**

The last stage of the framework consists of selecting the knowledge management process associated with each migration path. The knowledge transfer mechanisms illustrated by Argote (Argote, Ingram 2000) could be used as guidelines for identifying solutions suitable for each context, for instance by moving or modifying knowledge reservoirs.

The analysis of the case studies showed that when knowledge is transferred within the service phase the process could include an active role of the receiver, for instance service engineers pulling information from the reservoirs. On the contrary, when knowledge from service is expected to be reused by engineering designers, the knowledge management strategy needs to define how to push information to designers. Additionally, as in this case knowledge needs to be transferred across organisational boundaries, the knowledge management process has also to include a translation phase, in which the differences between service engineers and engineering designers are taken into account (Carlile 2004)

#### **5.4.5 Guidelines to the collaborating company**

The RSK model was adapted to the specific needs of the supplier of the drilling equipment that represented the main case study and resulted in guidelines to improve the company's way of handling information generated during service and documenting service cases. These guidelines are reported in Appendix 4.

### **5.5 Revised framework for defining a knowledge management strategy**

The general framework for selecting a knowledge management strategy that was followed in Section 5.4 to elaborate the RSK model, is hereby revised. It is integrated with factors that emerged from the interviews and were not explicitly taken into account in the initial framework.

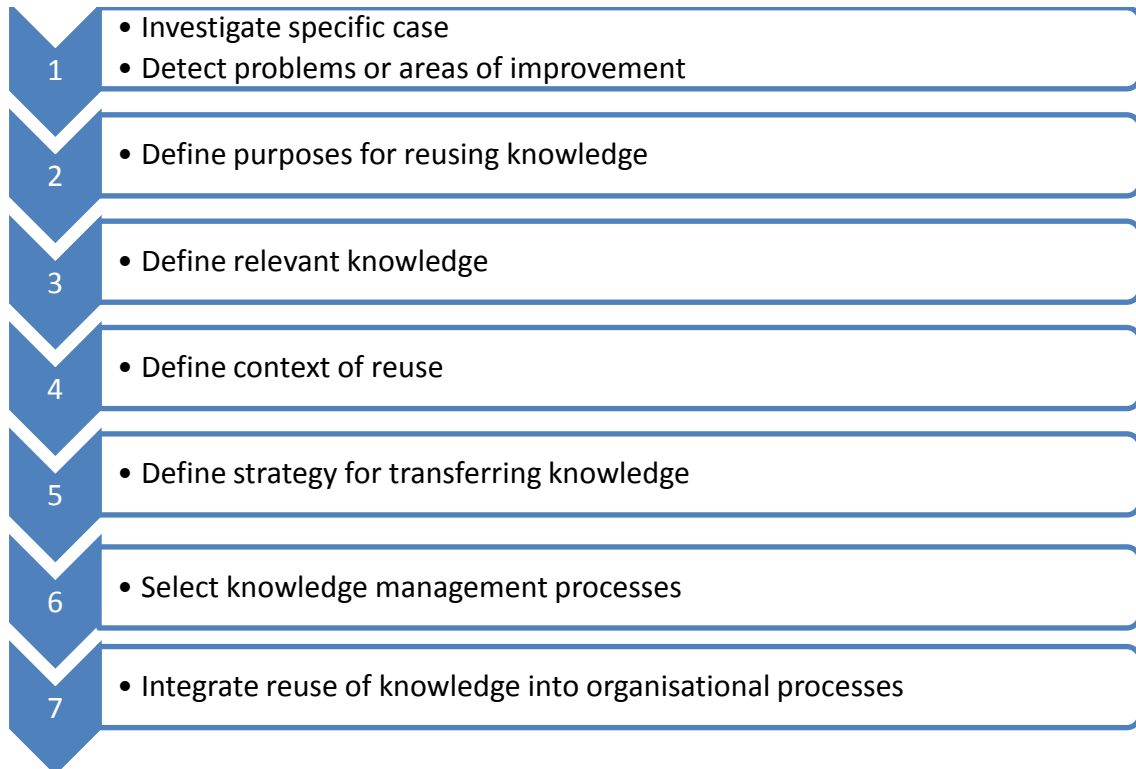


Figure 5.6 Framework for developing a knowledge management strategy targeting service knowledge.

The revised framework is summarised in Figure 5.6 and illustrated in the following sub-sections. The first stage corresponds to the problem identification in Kamara's framework (see Section 5.4.1), together with an in-depth investigation of the specific case in order to collect background information. Stages 2 to 4 clarify the factors to be taken into consideration while describing the to-be solution, such as the purpose of the strategy, the information relevant to be reused and the context of reuse. Stage 5 is focused on finding the migration paths and Stage 6 on the selection of knowledge management processes. Finally Stage 7, that does not have any correspondent in the initial framework, relates to integrating the knowledge management strategy into the overall organisational strategy.

These stages are described below together with their application to service knowledge.

### **5.5.1 Stage 1. Investigate the specific case and identify issues and areas of improvement**

Companies tend to adopt standardised solutions (e.g. software applications) in order to address their knowledge management needs (Robertson 2003); however this rarely leads to the expected results as the implemented tools do not take into consideration the characteristics of the specific company.

This fact is confirmed by the selected case studies. Despite the availability of documentation reporting service cases, when information was needed it tended to be retrieved through personal approaches or due to the support of a knowledge broker pointing to the relevant documentation. This is in agreement with other research studies (Marsh 1997), that indicate that people prefer to ask colleagues rather than retrieve information from knowledge repositories.

Hence the preliminary requirement for developing a knowledge management strategy is to investigate the specific case with regard to the characteristics of the organisation and its knowledge needs.

#### ***Application to service knowledge***

The choice of the knowledge management strategy for service knowledge needs to take into consideration a company's involvement throughout the product's lifecycle and its business model with respect to service, as these affect the knowledge from service available within a company and the motivation for reusing it. Additionally, the culture and organisational structure influence how knowledge is transferred within and across departments.

The case studies investigating complex customised products revealed that possible issues to target when developing a knowledge management strategy include: recurrent problems, the number of changes from the later phases of the product's lifecycle, the time required to close a service case, and product performances.

### 5.5.2 Stage 2. Define purposes for reusing knowledge

Once an overview of the specific case is obtained, the purpose of the knowledge management system needs to be defined, in accordance with the overall business strategy. In that respect, Zack (1999) suggested to identify the aims of the knowledge management strategy by highlighting a "strategic gap" through a SWOT (Strengths, Weaknesses, Opportunities, Threats) analysis. The crucial points of this analysis, first proposed by Andrews in the 1970s for developing a corporate strategy, are illustrated in Figure 5.7 (Andrews 1971).

Using the SWOT analysis to discover critical performance gaps helps align knowledge management initiatives with a company's competitive strategy. For example, performance gaps that are related to the management of service knowledge, such as quality problems and customer service issues, need to be corrected in order to achieve a high level of customer satisfaction.

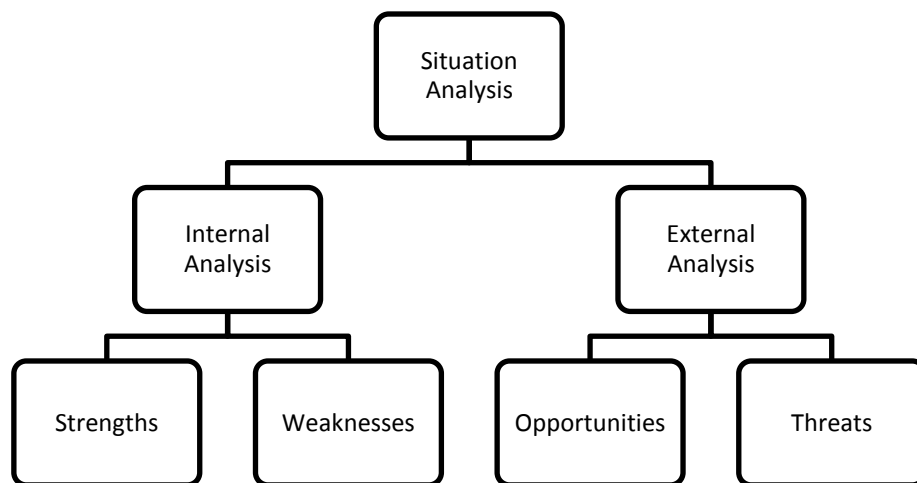


Figure 5.7 SWOT analysis (Andrews 1971)

Earl adopts a similar approach and suggests identifying the mismatches between a firm's capabilities and its intended or required strategy as the first step for designing a knowledge management strategy (Earl 2001).



### ***Application to service knowledge***

This stage aims to identify the motivation for capturing and eventually reusing knowledge from service. This is strictly related to the type of product supplied and the in-service support provided, as these influence the knowledge that is possible to collect and how it can be reused. The analysed case studies revealed two distinguishing factors influencing the motivation for capturing knowledge from service: external and internal factors.

Externals factors included:

- Requirements defined by regulatory bodies and legislation;
- Client requirements;
- Supplier requirements regarding guarantee claims.

External factors may lead to capturing information in a way that is not functional for its reuse. For instance, at the collaborating company documentation of changes was generated after a change was implemented in order to fulfil external requirements, and was not used during the trouble-shooting process or to support other change management processes.

Internal factors driving the capture of service knowledge are based upon a company's awareness of the value of the knowledge generated during the later phases of a product's lifecycle: a better management of knowledge helps answer the needs of the clients and represents a crucial factor for a product's success. From this perspective, two main purposes for capturing and reusing service knowledge were identified in the analysed case studies:

- Improving the in-service support provided with experience from past cases.
- Improving a product's design and performances (e.g. avoiding recurrent issues) by learning from its service and operation.

The capture of service knowledge motivated by external factors solely requires storing it into repositories making it available for external stakeholders. On the contrary, when the drivers for capturing service knowledge are internal, the knowledge management strategy needs to focus upon achieving an effective and systematic reuse

of the captured knowledge; otherwise efforts and costs for capturing this knowledge would be in vain, as knowledge stored in repositories but not reused does not bring any advantage to a company (except for legislative purposes).

### 5.5.3 Stage 3. Define relevant knowledge

Once the gaps between the organisational strategy and knowledge management programmes are identified, or in other words, the purpose of the knowledge management strategy is identified, it is necessary to define how a better reuse of knowledge could make a difference and evaluate the knowledge available against the identified purpose of knowledge reuse.

In general terms, knowledge can be categorised as (Zack 1999): declarative, procedural and causal knowledge, together with the supporting category of “know of” (see Chapter 3).

The choice of reusing one or the other type of knowledge leads to differences in the approach to handle the knowledge.

#### ***Application to service knowledge***

One of the problems with capturing and storing knowledge is that one does not know how, where or when that knowledge might be useful in the future (Wallace, Ahmed et al. 2005). This problem is even more apparent when a knowledge management strategy targets service knowledge, due to the long lifecycle of a product and the high variety of knowledge arising during service that make it difficult to foresee how this knowledge should be reused.

The characteristics of service knowledge have already been described in the literature review presented in Chapter 3. This section summarises the peculiarities of service knowledge that need to be taken into account when designing a knowledge management strategy targeted to this type of knowledge, in contrast to other knowledge.

- The approach towards service is different for different companies, as how a product is supported during its lifecycle, and consequently the knowledge

generated throughout this, is strictly related to a company's business strategy. This impacts the type of information captured and how to reuse it. Hence, when dealing with service knowledge, it is crucial to design a knowledge management strategy that is suitable for the company's business to take into consideration the needs of the users.

- In the case of the products investigated through the case studies, service knowledge is generated across a long time frame by a number of stakeholders, and is available from a variety of sources for a variety of aims. In contrast, design knowledge is created in a well-defined period and incrementally expanded with the specific aim of developing a product and manufacturing it. This makes issues related to how to capture and structure service knowledge more critical than for other types of knowledge.
- The reuse of knowledge is usually more difficult when it occurs across groups or departments. In the case of service knowledge these difficulties in transferring knowledge across organisational boundaries are more evident due to its distributed nature. Additionally, the motivations for reusing service knowledge are not easy to predict at the point when the knowledge is stored.

The three types of knowledge, declarative, procedural and causal, are hereby described in detail when referring to service knowledge. The additional "know of" category of knowledge is also employed to ensure that members of an organisation are aware of the existence of knowledge and are able to retrieve and reuse it.

Declarative knowledge describes objects, e.g. product, changes or performances. It represents knowledge that could be of interest beyond the context in which it has been generated, providing it is captured appropriately. This type of knowledge is easier to transfer across phases or cases. The case studies indicated that knowledge about product, changes and issues were the main types of knowledge from service that were of relevance to both service engineers and engineering designers. Hence a knowledge management strategy aiming to reuse service knowledge across departments, e.g. to improve the design of a product, should focus upon these types of knowledge.

Declarative knowledge can be captured and stored, usually in the form of drawings and documents, and retrieved using modern search engines that employ indexes, links and keywords.

Procedural knowledge is related to how to perform a task; it can be directly applied to a new task if the context of its validity is well defined, e.g. during trouble-shooting processes or while managing a project. However, it tends to be less general than declarative knowledge and mainly confined to a personal dimension. When it is captured into documentation (e.g. in the form of workflows, reports, manuals, procedures and project documents), its use is generally limited to one specific domain. In order to facilitate the reuse of this knowledge, the description of the actions performed, for instance during a service intervention, should be coupled with the explicit description of the rationale behind them (causal knowledge) and the product they refer to (declarative knowledge). This would help future users retrieve information, assess similarity between cases and utilise information beyond the defined case.

The analysed case studies highlighted difficulties in implementing standardised processes by using codified procedures, e.g.:

- It was difficult to search for documentation describing the processes that were followed in previous cases and then reuse this information while performing a task.
- Employees tended to elaborate their own way of facing a task based on their personal experience and posed resistance to the adoption of standardised procedures, particularly when they had not been involved in their development.

Causal knowledge refers to the reasons why something occurs. It can be captured in the form of rationale but it usually exists as implicit knowledge in the mind of engineering designers and service engineers. Currently the foremost research has focused upon how to capture causal knowledge during the design process with the aim of supporting designers, giving them access to (1) design strategies; and (2) design

rationale that characterises past projects. Designers are encouraged to record the reasons for their decisions in reports; however these reports are usually done retrospectively and often superficially. Acceptance decisions are recorded but the rejection decisions seldom are (Wallace, Ahmed et al. 2005).

From the literature survey and the case studies it emerged that no attempt has yet been made to capture the rationale behind the decisions taken in the service phase, neither in academia nor in industry.

Declarative, procedural and causal knowledge are simultaneously created while providing in-service support, as a service case generates knowledge related to:

- The problem and the solution (declarative knowledge);
- The process adopted to investigate a case, elaborate a solution and implementing it (procedural knowledge);
- The rationale behind the decisions taken (causal knowledge).

The types of knowledge relevant both within the service phase and across phases were declarative and causal knowledge describing issues emerging during service and their root cause, whilst procedural knowledge was only of relevance within the service phase to support trouble-shooting.

The types of knowledge targeted by the knowledge management strategy depend on the purposes that have been prioritised in the previous stage.

Reuse of service knowledge to improve product design: the focus is on efficiently capturing and reusing declarative knowledge to improve already existing but not systematised knowledge transfer practices. The capture of procedural and causal knowledge can be limited to the cases when it is motivated by external factors.

Reuse of service knowledge to improve the in-service support provided: the focus is on improving the capture of procedural knowledge and linking this type of knowledge to the declarative knowledge it is related to. This includes systematically reusing the process that led to the definition and the implementation of a solution, and verifying the rationale that justifies the decisions made.

#### 5.5.4 Stage 4. Define context for reuse

Once the knowledge gaps are identified and the types of knowledge that are wanted to be reused are selected, the senders and receivers, representing the stakeholders involved in the knowledge management process, need to be defined through the identification of:

- Knowledge sources;
- Knowledge transfer targets.

The definition of the context in which the knowledge is expected to be reused is a critical element for the development of the knowledge management strategy. This topic has not been widely investigated in research on knowledge management; however, more general studies on organisational learning (Carlile 2004) have highlighted differences in the way knowledge is transferred in homogeneous and heterogeneous groups. When the transfer is expected to take place across organisational boundaries a translation process is required in order to adapt available information to the understanding of the group receiving it. As shown through a separate study focusing on transfer of knowledge arising throughout the lifecycle of a product (Ahmed, Vianello 2009), the lack of clarity in determining where the captured knowledge is expected to be reused might result in a mismatch between the type of knowledge available and the need of the users and lead to the failure of the knowledge management strategy.

In general terms, the definition of how to reuse service knowledge includes the identification of:

- The level of the organisation at which the knowledge is of interest to reuse: e.g. group, department, or organisational level.
- The dimension of relevance: e.g. it is necessary to clarify whether knowledge about a project is to be reused within the project itself, across projects already in the operational phase or whether it is relevant for future projects. The same approach is valid in the case of knowledge about issues or products.

### ***Application to service knowledge***

The context in which the knowledge from service should be reused is influenced by the purpose of the knowledge management strategy. When service knowledge is expected to be reused to improve a product's design, the transfer has to take place across the organisational boundaries represented by the different departments. In this case it is necessary to define whether information is relevant for future products, products already in operation or any intermediate solution. Whilst, when service knowledge is expected to be reused to improve the in-service support, the knowledge management strategy has to take into account the needs of service engineers with regards to information storage and retrieval

#### **5.5.5 Stage 5. Define strategy for transferring knowledge**

Having identified the knowledge gaps that need to be closed, the knowledge that should be used in order to do it, and the senders and receivers involved, it is possible to complete the knowledge management strategy by selecting a suitable transfer method.

The two main strategies for transferring knowledge rely either on personalisation or on codification approaches.

Zack (Zack 1999) suggests that the choice between the two approaches has to take into account the degree of shared context between the sender and receiver. When the sender and receiver have a common understanding of the context a codification approach can be selected and electronic mediated channels used to facilitate knowledge transfer.

On the contrary, when the context is not well shared and knowledge is primarily tacit, personalisation approaches are easier to implement successfully (e.g. face-to-face conversation, forums).

Additionally other organisational characteristics, such as structure, culture, power relations or philosophy, affect the choice of the knowledge management strategy that is most suitable for a specific case.

### ***Application to service knowledge***

In the case of service knowledge generated throughout the lifecycle of complex products, such as drilling equipment, knowledge transfer through personalisation is not the optimal solution due to the high mobility of employees. A knowledge management model based upon codification suitable for this context has been described in Section 5.4.3 and summarised in Figure 5.5.

#### **5.5.6 Stage 6. Select knowledge management processes**

This stage is equivalent to the “Selection of knowledge management processes” described in Section 5.4.4.

#### **5.5.7 Stage 7. Integrate reuse of knowledge into organisational processes**

Knowledge management strategy and overall business strategy have to be consistent in order to achieve competitive advantage through knowledge management (Earl 2001). This consistency can be achieved through the definition of the purposes of the knowledge management strategy in the early phases of its development and the integration of this strategy into the organisational processes that specify when and how knowledge is captured, analysed and reused.

### ***Application to service knowledge***

In the considered case studies, the organisational processes (e.g. procedures and workflows) usually identified the knowledge that needed to be captured in documentation; however they did not describe how to reuse the available knowledge. In order to support the knowledge reuse, a knowledge management strategy needs to be linked to the organisational processes through:

- Defining when and how information should be reused;
- Assigning responsibility for each stage of the strategy (generation, validation, analysis).



## 5.6 Summary

This chapter focused on the definition of a knowledge management model suitable for the case studies taken into consideration and based upon the analysis of the current situation illustrated in Chapter 4.

In the first part of the chapter the framework proposed by Kamara was adopted to develop the RSK (Reuse of Service Knowledge) model that aims to support the reuse service knowledge for two distinguished purposes:

- Improving the service support provided;
- Improving the design of the next generation of products.

The core of the RSK model is the analysis phase that facilitates the reuse of available information by evaluating new information and, if possible, integrating it into documentation that is already available in a company's repositories.

In the second part of the chapter the process followed to develop the RSK model was analysed against Kamara's framework and the factors that emerged as relevant from the case studies but were not explicitly considered in Kamara's framework, such as the integration of the knowledge management strategy into organisational processes, were taken into consideration in a new framework for developing a knowledge management strategy targeted to service knowledge.

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## 6. Evaluation of the RSK model

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### 6.1 Introduction

This chapter focuses upon the evaluation of the RSK model developed in the prescriptive study. Since the RSK model could not be implemented within the time frame of the PhD project, an alternative way to evaluate it has been chosen and two dimensions have been evaluated, in accordance with Yin (1994):

- The internal validity of the RSK model within the company involved in the case studies.
- The external validity of the RSK model in other contexts.

The internal validity of the RSK model was tested through a workshop which involved both service engineers and engineering designers from the supplier of drilling equipment (see Section 6.2), whilst the external validity of the model was evaluated through a comparative analysis between the oil and aerospace industries that is described in Section 6.3. This choice of testing the results against a different context is in accordance with Eisenhardt's approach for building theories from cases (Eisenhardt 1989), which stresses the importance of generalising results for their applicability to different domains.

The validity of the results was evaluated following the five level evaluation model proposed by Ahmed (Ahmed 2000), that has been described in detail in Chapter 2. The internal and external validity were tested for reaction and validation; the methods adopted are summarised in Table 6.1.

Sections 6.2 and 6.3 first illustrate the methods chosen to evaluate the RSK model with regards to the internal and external validity respectively, then describe the results of the evaluation and finally discuss those results in relation to reaction and validation.

Table 6.1 Levels of evaluation of the RSK model.

	<b>Internal validity</b>	<b>External validity</b>
<b>Levels of evaluation</b>	Reaction, validation	Reaction, validation
<b>Methods</b>	Workshop with service engineers and engineering designers on how to reuse service knowledge	Comparison between oil and aerospace industries through the analysis of the service support provided

## 6.2 Internal validity

### 6.2.1 Methods

The internal validity of the RSK model was tested through a workshop conducted at the supplier of the drilling equipment, in which two service engineers and five engineering designers were involved.

The workshop aimed to capture the needs and suggestions of the participants in relation to the reuse of knowledge from service, and to compare these to the RSK model that is described in Chapter 5. The workshop was composed of three parts:

- Introduction to the topic;
- Brainstorming session on service knowledge and its reuse;
- Comparison of the results from the brainstorming session to the RSK model.

In the first part of the workshop the importance of improving the company's knowledge management practices was introduced to the participants through examples of poor reuse of service knowledge that were elicited from the interviews. General areas of improvement related to knowledge management were also presented: e.g. monitoring operating conditions and performances during service to achieve preventive maintenance.

The brainstorming session, that represented the main part of the workshop, was developed based upon the stages characterising a service case that were captured into the RSK model, namely:

- Problem solving phase;
- Implementation of the solution;

- Capturing of knowledge from the case;
- Reusing of available knowledge.

The participants were involved in the discussion of an issue that was likely to occur during service by going through each of the above stages. The brainstorming was carried out following the “how might we” technique frequently used in design (Brown 2009) and the participants were asked to see themselves in an ideal system with all knowledge potentially available, without the limitations of existing systems or communication practices in use at the company. Part of the presentation used to support the brainstorming session is in Appendix 5.

After the brainstorming session, the RSK model was discussed with the participants and the fitting of the results from the brainstorming into the proposed model was evaluated.

The reaction of the participants towards the RSK model was evaluated by assessing their ease in adopting the stages of the RSK model as a framework to analyse the fictional case, whilst the RSK model was validated by evaluating the compatibility of the outputs of the brainstorming session with the model itself.

### **6.2.2 Results from brainstorming session**

This section presents the outputs of the brainstorming session, dividing them into three main areas:

- Outputs related to reusing service knowledge within service;
- Outputs related to reusing service knowledge in product development;
- Outputs related to capturing and transferring service knowledge.

#### ***Reusing service knowledge within service***

The part of the brainstorming session that investigated the reuse of knowledge within service focused upon how service engineers would like to access knowledge from past service cases during a service intervention. The service engineers indicated that they would like to have an overview of the stages of the trouble-shooting process that characterised relevant cases, from the description of the problem to the definition of

the solution (Figure 6.1). The service engineers stressed their need of retrieving documentation describing not only the issue but also the context in which the issue arose (e.g. type of rig, wear conditions, operation mode etc.) and the reasoning behind the selected solution in order to be able to assess similarities across cases and determine whether the solution adopted in a previous case could be applicable to the one still open. The participants suggested that capturing the process that was followed and structuring it in the form of a checklist could provide valuable support for handling future service cases and result in faster and more consistent in-service support.

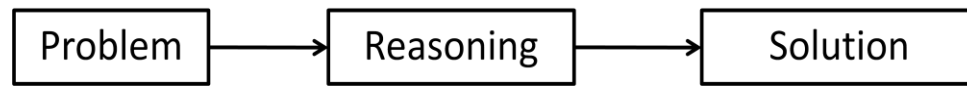


Figure 6.1 Phases of the trouble-shooting process relevant for service engineers.

### ***Reusing service knowledge in product development***

A further purpose of the brainstorming session was to understand how engineering designers would like to use information from service when developing a new product. During the workshop the engineering designers confirmed their interest in knowledge about issues, however they indicated the necessity to distinguish between: (1) knowledge on moderate recurrent issues or ideas for improvement and (2) knowledge on severe problems, as these two types of knowledge needed to be captured and fed back to them in different ways (see Figure 6.2).

In the case of severe problems occurring during service, engineering designers were made immediately aware of the problems through personal communication and being involved in the definition of the solution. This aided them to take severe problems into consideration when designing a new product, as they were already aware of them.

On the contrary, moderate issues or ideas for improvements from service were not systematically fed back to engineering designers, as engineering designers were not involved in the definition of the solution. At the same time, engineering designers did not actively search for information about service issues whilst developing a new product as they did not have the time and the background knowledge to take into

consideration all the documentation of moderate issues or possible improvements; hence this type of information was not considered in the development phase. The aggregation of reports from similar moderate issues was suggested as a way to reduce the load of information potentially available to designers and help them focus upon cases with a high rate of occurrence. Engineering designers were not interested in individual cases of moderate issues, but they would like to access service information in the form of e.g. ranking of most common issues, failure rate, and performance data. Additionally, a comparison of performances of different components and sub-components that are common across products was also mentioned as useful information to support designers during the development process or when selecting suppliers.

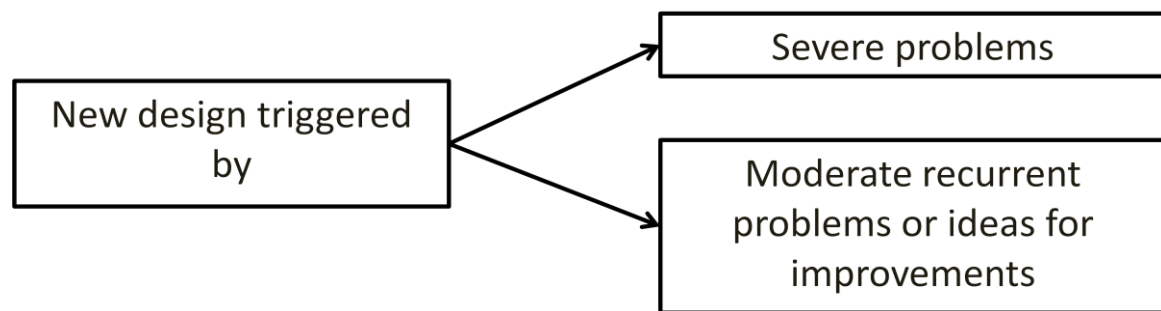


Figure 6.2 Drivers of new design solutions.

### ***Capturing and transferring service knowledge***

The last purpose of the brainstorming session was to elicit how the participants wanted service knowledge to be captured and structured in order to satisfy their needs for reusing it. The participants were explicitly asked to describe how they would like information to be organised.

They highlighted their current difficulties in searching for relevant documentation and suggested that having a well defined documentation structure, which allows an easy identification of the information relevant for a specific case, would facilitate the reuse of codified knowledge. For instance the distinction between *problem*, *troubleshooting* and *solution* needed to be taken into consideration in the structure of documentation.

The participants confirmed the importance of indexing service cases against criteria like *product* and *issue*; in addition they suggested other operative criteria specific to the industry that could be useful to search for relevant information, e.g. *project*, *rig* or *date* of the service intervention. Furthermore, an early classification of a service case also against its severity, distinguishing between severe and moderate issues, would be useful in order to handle information about service cases in two different manners.

A further element that the participants considered critical for the reuse of documentation was how a service report was followed up, as they stressed the importance of validating available documentation in order to build the trust of the users. Various ways to increase this trust on documentation were mentioned, including:

- Defining clear ownership of the information, assigning a person responsible for following up each case, e.g. by coordinating the actions required in the long run or providing details and clarifications when requested.
- Integrating valuable information from service case into existing official documents such as manuals (e.g. when the information is expected to be reused within service).
- Updating the product masters that are used as a starting point for next design with information of changes (e.g. when the information is expected to be reused when designing new products).

The brainstorming session also showed the preference of the participants for transferring information of service cases through personalisation strategies (e.g. meetings), particularly when it was a matter of recurrent minor issues or ideas or improvement. The participants suggested feeding information regarding moderate recurrent issues back to a new established change board or a product improvement board that would be in charge of coordinating the company's actions towards open cases. Table 6.2 provides a summary of the results of the brainstorming section.



Table 6.2 Summary of the results from the brainstorming session

	<b>Inputs from brainstorming</b>	<b>Issues addressed</b>
<b>Reuse of service knowledge within service</b>	<ul style="list-style-type: none"> <li>• Service engineers would be aided by the retrieval of information from past cases, if this information was available through a standard, well structured document that covers all the phases of a service intervention and provides information about the context in which a service case occurred.</li> </ul>	<ul style="list-style-type: none"> <li>• Fragmented documentation did not allow service engineers to obtain a clear picture of past service case and assess similarity between cases.</li> </ul>
<b>Reuse of service knowledge in product development</b>	<ul style="list-style-type: none"> <li>• Making service information available to designers in the form of e.g. ranking of most common issues or failure rate would facilitate the reuse of information about moderate recurrent issues during the development process.</li> </ul>	<ul style="list-style-type: none"> <li>• Engineers only took into account severe issues. They were not informed of moderate recurring issues and they did not search for this type of information due to information overload.</li> </ul>
<b>Capturing and transferring service knowledge</b>	<ul style="list-style-type: none"> <li>• The implementation of search criteria like product, issue, rig, etc. would facilitate the retrieval of documentation.</li> <li>• Nominating a person responsible for documenting a service case and capturing information from service cases into validated documents (e.g. user manuals, product masters) would increase the trust in documentation.</li> </ul>	<ul style="list-style-type: none"> <li>• Relevant documentation was difficult to access.</li> <li>• Often documentation was not completed and validated, hence generating a lack of trust for the users in available documentation.</li> </ul>

### **6.2.3 Evaluation of reaction and validation**

The workshop with service engineers and engineering designers was used for multiple purposes. The first part focused upon presenting the research project to practitioners and capturing their views on the topic.

In the brainstorming session a fictional service case was analysed following the stages of the RSK model in order to:

- Assess the easiness for the practitioner to analyse a service case following the same stages that constitute the RSK model, hence evaluating their reaction to the model.
- Verifying that the solutions proposed by the practitioners during the brainstorming session were compatible with the RSK model presented in the prescriptive study, hence validating the model.

The evaluation of the RSK model with respect to reaction and validation is presented in the following paragraphs.

#### ***Reaction***

The participants in the workshop reacted positively to the research project and its overall purpose of improving the reuse of service knowledge, as they perceived the transfer and reuse of available knowledge as an important issue that the company had to face.

The reaction of the participants towards the RSK model was tested by following its constituent stages to investigate a fictional issue from service. The model was compatible with the participants' way of approaching the issue from service, as they followed its stages to analyse the case with ease. Additionally, the participants accepted the distinction between knowledge that is expected to be reused within service and knowledge that is relevant to reuse whilst developing new products. They also confirmed the main issues that emerged from the analysis of the case studies, e.g. the lack of structure in documentation and repositories and the fact that engineering designers were only aware of service issues pushed to them.

### ***Validation***

The prescriptive study described in Chapter 5 aimed to answer the last of the research questions identified in Chapter 1:

- How can the current situation be improved in order to obtain a systematic reuse of knowledge from service?

The answer to this question was synthesised in the RSK model.

The brainstorming session indicated that the service knowledge that the participants wanted to be made available in order to support product improvement was related to severe or recurrent problems. In the case of moderate recurrent issues, the participants suggested to aggregate similar cases in order to evaluate the rate of occurrence of a problem and take action when needed.

The investigation of how the participants wanted to reuse service knowledge confirmed the transfer mechanisms identified from the interviews and allowed receiving feedback on the RSK model proposed to facilitate the reuse of knowledge from service.

The importance of processing codified knowledge in order to facilitate its reuse was confirmed by the participants that suggested integrating new information from service into, for instance:

- Manuals, if information is expected to be reused within service,
- Product's masters, if information is expected to be reused during the design process.

The difficulties in reusing information about moderate issues or ideas for improvements led the participants to suggest that this type of information needs to be handled differently; for instance the reports from similar service cases need to be analysed, grouped together, and then evaluated during board meetings where it is decided how to address the issue.

During the brainstorming the trust of the users in available documentation was found to be a critical factor for the reuse of information. The fact that information was often incomplete and scattered across repositories undermined the trust of service engineers

and engineering designers in the documentation and motivated the participants to suggest measures to build trust, such as assigning a person responsible for the follow up of a case and to capture relevant information into more stable forms like manuals. The RSK model answers this need of generating trustworthy sources of information through the analysis phase, when processed information is generated, as analysing information initially captured into a variety of service documents and making it available in a form that is directly applicable to other contexts helps increase the trust of the employees in documentation. The analysis phase can also be used to distinguish severe problems from minor problems or ideas for improvements, and identify how each case needs to be followed up.

### ***Comments***

The workshop carried out at the supplier of drilling equipment evaluated the internal validity of the RSK model with respect to the *reaction* of the practitioners and *validation*. Like the RSK model, the workshop was focused upon the reuse of one specific type of knowledge, knowledge about issues and changes. This choice was motivated by the fact both the case studies and literature (see Chapter 3) indicated knowledge about issues, changes and improvements as the prevalent knowledge from service that is relevant for both service engineers and engineering designers.

The participants showed a positive reaction to the RSK model and adopted its stages to analyse a service case with ease. Additionally, their suggestions on how to improve the reuse of service knowledge were compatible with the RSK model. Although some of the initiatives suggested during the workshop, such as the distinction between severe moderate problems and the need for building trust in documentation, were not described in detail while developing the RSK model, the model allows taking them into account.

## **6.3 External validity**

The external validity of the results was informally tested through a presentation of the research project to industrial practitioners from various types of industry. This

presentation was given by a colleague during the Gensynsdag (Alumni day) at the Technical University of Denmark in 2009. The feedback received was positive.

Subsequently, the external validity was more thoroughly tested through an auxiliary case study carried out in collaboration with an industrial researcher from the University of Bath. The case study focused upon the investigation of the service support provided within the aerospace industry.

The results from the auxiliary case study were then compared to the case studies from the oil industry and similarities and differences discussed. The stages followed to test the external validity of the RSK model are summarised in Figure 6.3.

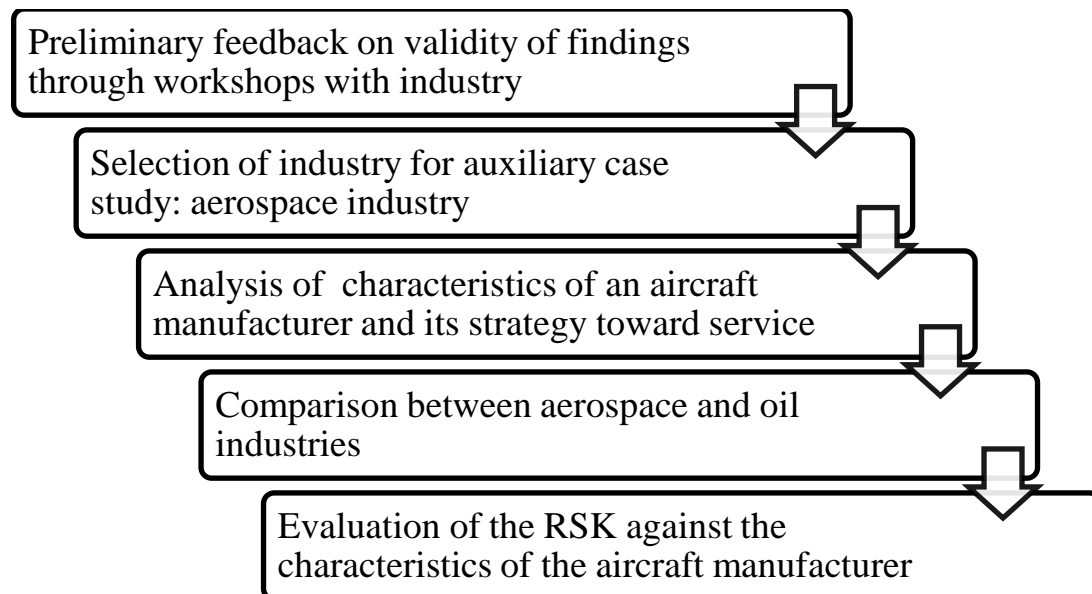


Figure 6.3 Stages for evaluating the external validity of the RSK model described in Chapter 5.

The evaluation of the external validity of the RSK model through the auxiliary case study is described in detail in the sections to follow. Section 6.3.1 illustrates the reasons for choosing the aerospace industry to test the external validity of the RSK model and presents the methods adopted for carrying out the auxiliary case study. Section 6.3.2 describes the results of the auxiliary case study, whilst Section 6.3.3 compares these results with those from the oil industry. Finally, Section 6.3.4 discusses the external validity of the RSK model by relating it to the needs for knowledge reuse that characterise the aerospace industry.

### **6.3.1 Methods**

The RSK model was developed based on the analysis of the current practise in the oil industry. In order to evaluate its validity beyond the specific case, an auxiliary case study was carried out in collaboration with an aircraft manufacturer and the RSK model was compared to how service knowledge was reused in the aerospace industry. This comparison focused on the reuse of service knowledge within the service phase, as the long development time that characterises the development of new products in the aerospace industry posed a barrier to the investigation of the reuse of service knowledge during the design phase.

This section first illustrates the motivation for choosing the aerospace industry for the auxiliary case study, then describes the research methods that were adopted for analysing the service support provided by the aircraft manufacturer and the reuse of knowledge from past service cases during in-service support.

#### ***Case selection***

The aerospace industry was selected as a suitable domain for the auxiliary case study, due to the balance between similarities and differences between the aerospace and oil industries.

On the one hand, the aerospace industry, like the oil industry, deals with complex products. Additionally, both the industries do not admit failure of their products during operation and have to keep track of issues and requests for changes arising throughout all the phases of the product's lifecycle due to international regulations and strict client's requirements.

On the other hand, the two industries are characterised by different development and production processes. Aircrafts, and their components such as the aeroengine, are examples of a variant design domain, with new designs that often reuse modules from past variants. Whereas the drilling systems developed for offshore oil rigs are characterised by different combinations of customised equipment; hence, the final configuration of the drilling system is unique for each rig. In the oil industry the testing phase is limited and takes place after the equipment has been built due to the

one-off nature of the drilling equipment; in contrast in the aerospace industry the testing and prototype phase precedes production. The development processes that characterise the aerospace and oil industries are illustrated in Figure 6.4 as part of the product's lifecycle.

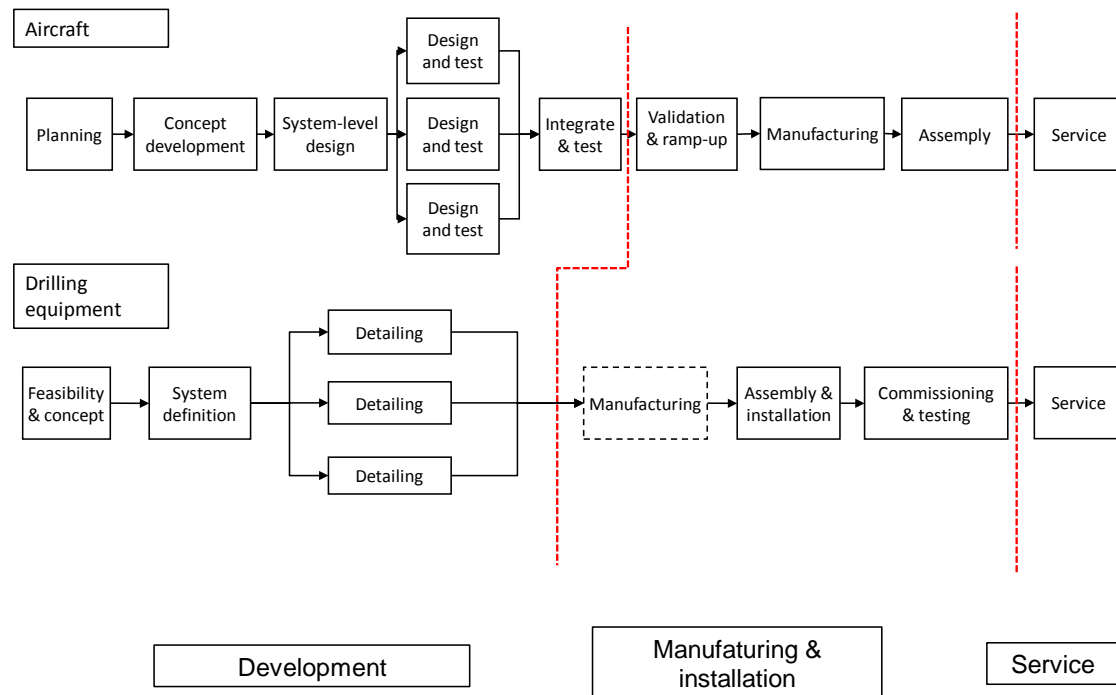


Figure 6.4 Schemes of the lifecycle of the aircraft and the drilling equipment. In the case of the aircraft, testing is part of the development of the product, whilst, in the case of drilling equipment, it occurs after manufacturing. Additionally the supplier of drilling equipment outsources manufacturing to sub-suppliers, hence the dashed box for the manufacturing phase.

The aircraft manufacturer was taken into consideration with regard to the support provided during service – in-service support according to the company lexicon – and how this process was facilitated by the reuse of available documentation. The analysis of the in-service support provided was based upon data from different sources. The methods adopted for data collection and analysis are described in detail in the following paragraphs.

### ***Approach toward in-service support***

The auxiliary case study aimed to describe the characteristics of the aircraft manufacturer and its approach towards service, as it was done in Chapter 4 for the supplier of drilling equipment. The in-service support provided by the aircraft manufacturer was investigated through a participatory research approach, in collaboration with Yifan Xie, an industrial researcher from the University of Bath who was conducting his PhD project in collaboration with the aircraft manufacturer. He contributed to the project by providing information on the company background and empirical evidence already collected. Additionally he participated in collecting further evidence through interviews with service engineers, the analysis of the procedures related to the in-service support provided and the investigation of the repositories used to store information about service cases. Yifan Xie was also involved in the analysis of the data. The data collected are summarised in Table 6.3.

The in-service support group that participated in the research study was in charge of answering repair requests, whilst it was not involved in providing other forms of support such as preventive maintenance that, consequently, have not been taken into account in this study.

Table 6.3 Data collected at the aircraft manufacturer.

<i>No. of interviews</i>	<i>No. of information systems analysed</i>	<i>No. of procedures analysed</i>
<b>7</b>	<b>12</b>	<b>2</b>

### ***Reuse of service knowledge***

During the initial dialogue with Yifan Xie, the RSK model was discussed and the focus of the collaboration was defined. The dialogue resulted in the development of a framework representing the ideal lifecycle of service knowledge, that was then used in the analysis of how service knowledge was reused at the aircraft manufacturer (see Figure 6.5).



According to the proposed framework, the knowledge generated during in-service support *practice* is captured in *documentation* describing the case. Consequently, this documentation is *processed* and, if possible, integrated into already existing documentation, in order to facilitate its application to other cases. Figure 6.6 links these stages to the RSK model.

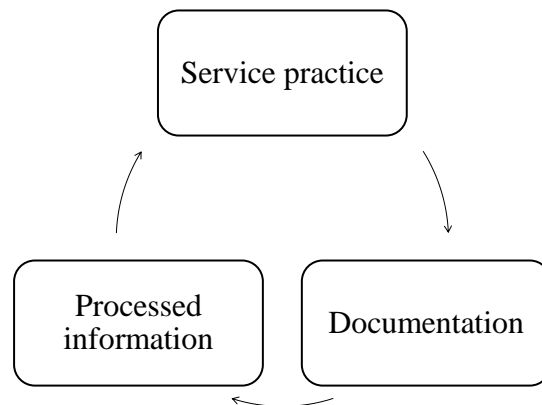


Figure 6.5 Framework of the lifecycle of service knowledge used to analyse the data from the aircraft manufacturer.

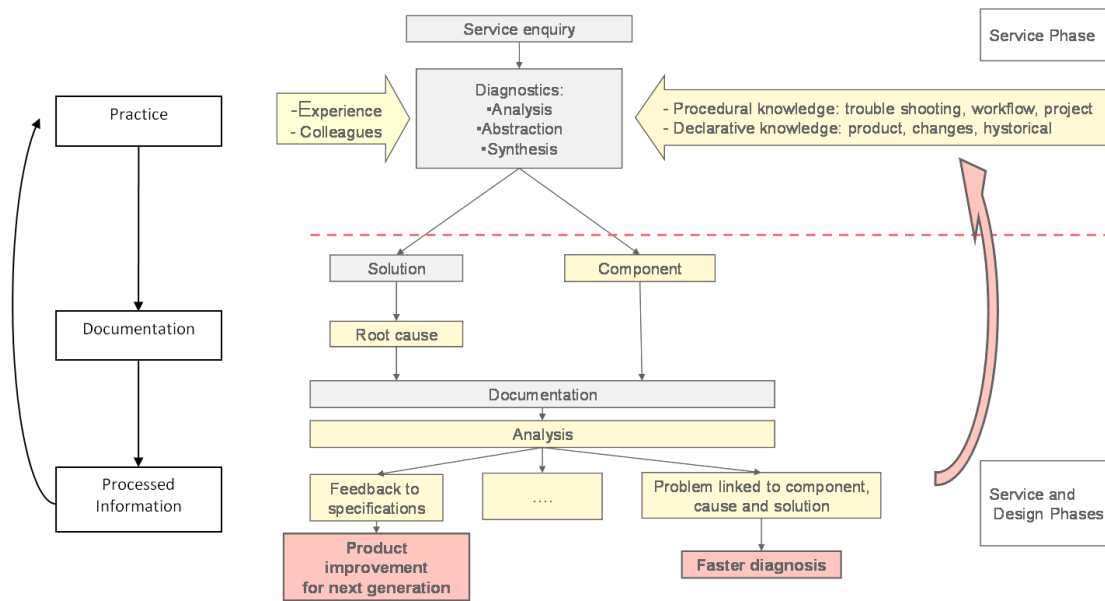


Figure 6.6 Practice, documentation and processed information in relation to the RSK model proposed in Chapter 5.

### 6.3.2 Results from the auxiliary case study

The sections to follow describe the aircraft manufacturer representing the auxiliary case study in relation to the in-service support the company provides to their clients and how service knowledge is generated, captured and retrieved during the in-service support process.

#### *In-service support provided*

A general description of the main features characterising the aircraft manufacturer, particularly in relation to its strategy towards in-service support, is hereby provided with the aim to illustrate the context in which service knowledge is reused. This background information is important when comparing the two industries.

The aerospace company taken into consideration produced civilian and military aircrafts. The company developed and produced a wide range of aircraft models; the typical development cycle of a new model, from the early feasibility studies to the entrance into service, required about 15 years. The aircrafts were made-to-order, i.e. their production was subsequent to receiving an order request from airline operators.

The company had a central customer service department which acted as a focal point for all inquiries from airlines. This research specifically focused on repair requests whilst other types of in-service support were not investigated. The requests for repairs were forwarded to the relevant group within the in-service support department, as each group was dedicated to servicing specific parts of the aircraft. The in-service support department provided support on a 24-hour- a-day, 365-day-a-year basis to design and validate repair requests arising from airlines. The repair requests were principally of two types:

- Major repairs, requiring significant support such as the direct involvement of a service engineer from the aircraft manufacturer in the repairing process.
- Simple repairs, resulting in providing the airline with repair instructions to implement, usually without the need of having a service engineer from the aircraft manufacturer performing the job.

Simple repairs represented the majority of the repair requests and were the main focus of the case study.

### ***Reuse of service knowledge***

This section describes how the aircraft manufacturer reused available knowledge when handling a new service case; the description is based upon the data collected and is organised according to the framework *processed information-practice-documentation* that was illustrated in Section 6.3.1. The following section (Section 6.3.3) compares what emerged from the analysis of the aircraft manufacturer with the characteristics of the supplier of drilling equipment that were illustrated in Chapter 4.

### **Processed information: procedures and standard solutions**

An official procedure was developed at the aircraft manufacturer to describe the workflow to follow when providing in-service support. This procedure prescribed how to handle a service case and described the steps to follow, including the instructions on the information that needed to be captured in documentation. However

it did not indicate how to retrieve and reuse information from past cases, despite this it was perceived from the interviews as an important factor to ensure a quick response.

In addition to the official procedure which was recognised at a company level, one section of the service department had also developed its own unofficial procedure; this was derived from the section's best practices for handling a service case and described in more detail the part of the workflow where the section was involved.

Together with the procedure describing how to provide in-service support, standard repair manuals with instructions for generic repairs were made available by the company for both internal and external use. These generic repair instructions were elicited by senior engineers based on their experience on recurrent cases.

### **Service practice**

The service practice was investigated dividing it into three phases:

- 1) Case identification;
- 2) Trouble-shooting and implementation of the solution;
- 3) Closure of a service case.

Each of the phases is described in detail in the paragraphs to follow.

#### *1) Case identification*

The customer support centre was the point of contact for airline operators to raise in-service support requests. It forwarded these requests to the part of the in-service department responsible for servicing the part in question (e.g. wing, landing gear, fuselage).

#### *2) Trouble-shooting and implementation of the solution*

The in-service department employed two types of service engineers: repair design engineers in charge of designing the repair method, and stress engineers in charge of validating the repair method. The two groups were managed respectively by senior design and senior stress engineers. When a repair request was received, the typical in-service support workflow included five stages: (1) the case is assigned to a repair design engineer and a stress engineer; (2) the repair design engineer proposes a repair

method for the reported damage; (3) the stress engineer validates the repair method with regard to stress and fatigue; (4) senior design engineer and senior stress engineer examine and eventually approve the repair method; and finally (5) the approved method is fed back to the customer service in the form of repair instructions, ready to be forwarded to the airline operator for implementation.

The interviews with members of the in-service department highlighted that the experience of service engineers was the most important factor to elaborate the repair method on time, as it influenced how to efficiently search for past cases and reuse the retrieved information in the most effective way.

### *3) Closure of the service case*

The operator, after having implemented the solution, had to provide feedback to the aircraft manufacturer in order to receive formal approval of the repair work. Once this had taken place, the service case was formally closed.

## **Documentation**

The last element constituting the framework to analyse the reuse of service knowledge is the capture of *service practice* into *documentation*. Information related to tasks such as designing or validating a repair method was often scattered across repositories, and required a significant amount of time for service engineers to search for it. A project to allow accessing information from different sources through a single interface was ongoing at the time of data collection. Both repair design engineers and stress engineers used the indications included in the documentation from past cases for understanding what information was needed and where it was stored.

## **Comments**

The reuse of past experience, while defining the solution for a service case, was common practice at the collaborating company, as well as prescribed by both official procedure and best practice. However, several barriers against the systematic reuse of service knowledge were identified while investigating the case; they will be discussed

and compared to the barriers that characterised the case studies from the oil industry in Section 6.3.3.

The engineers who were interviewed indicated that factors that could help them reuse information from past cases while performing their job included:

- Systematically reviewing recurring repair cases. For example, using standardised methods to categorise repair cases and setting up regular meetings to review them.
- Improving communication and inter-learning across in-service departments, and standardising the use of official procedures across different departments.
- Improving the search facility of the repositories to allow cases to be compared.
- Providing detailed guidelines on how to facilitate searching for information.

### 6.3.3 Comparison with the oil industry

The results from the case study from the aerospace industry are hereby compared to those from the oil industry, described in Chapter 4. The fundamental differences between the two cases are summarised in Table 6.4 and discussed in the following sections.

Table 6.4 Differences between the aerospace and oil industry with respect to the in-service support.

	Aerospace industry	Oil industry
<b>Type of in-service support provided</b>	Service engineers provide remote support.	Service engineers are often sent on site.
<b>Validation of repair solution</b>	If predefined solutions are not applicable, the proposed solution has to be validated by stress engineer.	Validation from product responsible is not systematic and often follows the implementation of the solution.
<b>Task allocation</b>	Senior service engineer assigns a case to service engineer who suggests a solution.	Senior service engineer supports service engineers during the service case.
<b>Info and knowledge flow</b>	Communication mediated by customer support both ways.	Direct contact between service engineers and client while providing the solution.
<b>Level of codified documentation</b>	Standard documents describing problem and solution.	Case documented according to type of case and people involved.
<b>Reuse of past cases</b>	Information from past cases is captured in manuals in the form of predefined solutions.	Not systematised.

### 1) Type of in-service support provided

The analysis of the case studies showed that companies from both the oil and the aerospace industries, namely the supplier of the drilling equipment and the aircraft manufacturer, were involved throughout the lifecycle of the products they developed by providing a similar type of in-service support (e.g. maintenance, repairs, spare parts). However, their strategies towards the organisation of the in-service support provided and the reuse of information from past cases were divergent: the aircraft manufacturer adopted a codified approach, while the company supplying drilling systems was characterised by more personal approaches. These differences may have been motivated by diversities in:

- Product: more standardised in the case of an aircraft compared to a drilling system.
- Development process: the drilling equipment was designed-to-order according to the client's requirements and tested only after manufacturing, often under time constraints. On the contrary, the development of the aircraft was characterised by thorough testing in order to detect and correct any design fault before the aircraft's ramp-up.

Two types of service strategies have been elicited from the cases. The in-service support supplied by the aircraft manufacturer was generally characterised by relatively low variety, achieved by dividing the service department into sections dedicated to servicing a specific part of the aircraft. The communication between aircraft manufacturer and airline was highly formalised and any repair solution was validated before its implementation. These characteristics allowed the choice of remote support as the preferred type of in-service support and resulted in a reduction of the time required for handling a service case. However, necessary pre-requisites for the adoption of this strategy are the availability of the expertise needed to implement the solution outside the service department and a way of capturing service issues that provides service engineers with the information necessary for a correct evaluation of a case.

The organisation of the in-service support at the supplier of drilling equipment was different. The service cases were characterised by high variety – due to the customised nature of the drilling systems and the company’s choice not to have service engineers specialised in servicing a specific type of equipment – and the support provided was based upon the dialogue between client and supplier during problem identification and the implementation of the solution. An increased level of remote support would result in advantages both in terms of time and costs. However, the company would need to adopt a systematic process for validating the solution before its implementation, as the current trial and error model would no longer be applicable. Additionally, problems in relation to the implementation of the solution may occur due to the lack of competent personnel on the rig.

## 2) Validation of the repair solution

It was imperative for the aircraft manufacturer to implement an acceptable repair solution at first and no errors were allowed, in compliance with the strict regulations of the aerospace industry. This motivated the rigorous process of validating a repair solution before its implementation. Moreover, the adoption of a standard way of capturing information about a service case and transferring it between the service engineering department and the customer support resulted in positive effects such as:

- Systematic and consistent storing of service cases into knowledge repositories;
- Increasing trust in information available from the company’s repositories, as it was validated before being stored.

On the contrary, most of the failures in the drilling equipment on an oil rig resulted in extremely high costs of downtime, but did not compromise the safety of the people on board. This led service engineers to try to find a solution in the fastest possible way, which in most cases resulted in accessing information on past cases through personalisation strategies and elaborating the solution by trial and error through an iterative process. The need for a detailed record of the work performed was less urgent than in the aerospace industry, as during the warranty period the supplier of



drilling equipment was directly involved in the implementation of the solution of a service case. Although this approach based upon the personal experience of a service engineer could lead to short-term positive results, it was not beneficial in the long-term, as it resulted in a non-homogeneous quality of the service provided and in limited learning from past cases.

### 3) Task allocation

At the aircraft manufacturer the adoption of a standardised validation process allowed giving the less experienced service engineers the responsibility of proposing a repair method. In this context, senior service engineers did not have to monitor the development of service cases and could cover a managerial role, e.g. by developing standardised repair methods.

At the manufacturer of drilling systems, senior service engineers were actively involved in the progression of service cases by providing service engineers a description of the job to perform and supporting them while on site. This more active involvement of senior positions in providing in-service support was a way of validating the decisions taken by service engineers without implementing a formal validation process.

### 4) Knowledge flow

In the case of the aircraft manufacturer, the customer support centre represented the interface between the company and its clients across the different phases of the in-service support. This organisational choice was motivated by the internal complexity of the company: the customer support centre had to coordinate the different sections of the service department and supply a standardised in-service support to the customers, no matter which part of the aircraft was involved.

In contrast, the supplier of drilling systems prioritised the provision of on-site support performed by a member of the service department. After receiving the service inquiry through the customer support centre, the approach towards service that was adopted was based upon the dialogue between the service engineer assigned to the case and

the client, and did not generally include a formal validation process to be completed before implementing a solution.

#### 5) Level of codified information

At the aircraft manufacturer the customer support was responsible for mediating the communication between service engineers and the airlines throughout the different phases of the in-service support. This organisation of the in-service support required the use of a standardised way of handling service cases, particularly when capturing the documentation generated during the process and providing the solution to the client.

The more personal approach towards service of the supplier of drilling systems limited the need for documentation when handling a service case and resulted in reports from service being completed only after the closure of the case, often not thoroughly and with poor consistency across cases. Both the cases showed issues related to capturing information of service cases, particularly:

- The way of capturing information changed throughout a product's lifecycle in terms of both the type of information captured and where it was stored;
- Different repositories were available for storing information (e.g. drawings, emails, reports);
- The companies' procedures on how to generate and use documentation were general. Inconsistency emerged in how these procedures were put into practice by different sections.

#### 6) Reuse of service knowledge

The framework *practice-documentation-processed information* describing the ideal lifecycle of service knowledge that was described in Section 6.3.1 is hereby compared to how service knowledge was reused by the supplier of drilling equipment and the aircraft manufacturer. The framework was based upon the distinction between documentation from single service cases and processed information (procedures, standard solutions) generated from the analysis of similar cases; the latter type of

information being more effective to support service engineers while solving a new service case. Figures 6.7 and 6.8 summarise the main barriers for a systematic reuse of information from service that emerged from the analysis of the two industrial cases; these barriers included difficulties in assessing similarities between cases and the lack of a standardised way to generate processed information.

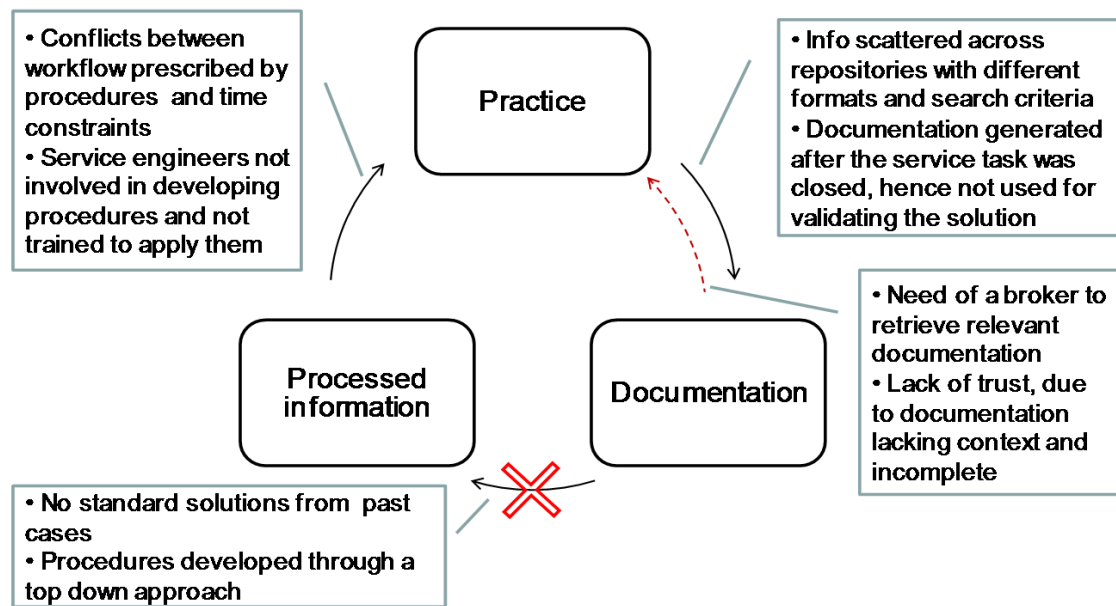


Figure 6.7 Barriers to the reuse of service knowledge in the case of the drilling equipment.

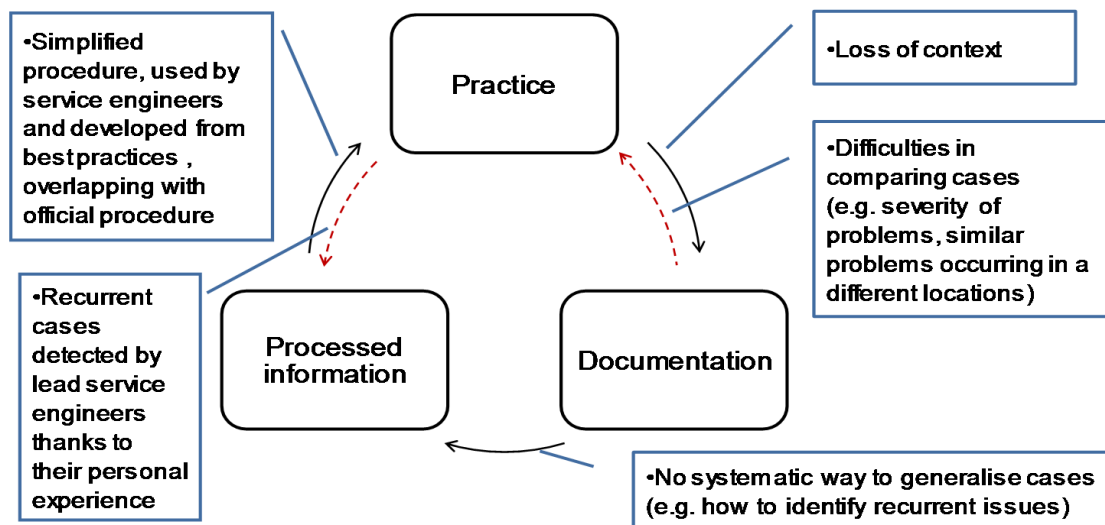


Figure 6.8 Barriers to the reuse of service knowledge in the case of the aircraft.

At the aircraft manufacturer the reuse of documentation from past cases represented common practice and was included in the formal procedure describing the in-service support workflow. However, the procedure did not include how to search for relevant cases. Past cases were reused in two distinguishing manners:

- By reusing the solution already adopted in a previous case;
- By reusing the process followed to generate or validate the solution of a previous case.

The supplier of drilling systems reused past cases mainly through the personal experience of service engineers. When documentation from past cases was reused, it was retrieved by people already aware of the case or as a result of a suggestion from a colleague.

Both cases showed difficulties for service engineers to obtain useful information from available documentation, as documentation often included redundant information, which was not relevant beyond the specific case for which it was written, and lacked information about context, important to compare cases. A critical task was the assessment of the similarities between cases in order to understand how experience from a past case could be reused while working on a new case. This problem was equally relevant for the two cases with respect to comparing issues, while it was more

significant for the oil industry when it involved comparing products, due to the customised nature of the drilling equipment.

Standard solutions, in the form of repair methods, were available to service engineers at the aircraft manufacturer. These solutions, which could be adopted without further validation, were developed from the analysis of recurrent past cases (see Figure 6.9) and included the description of the range of cases that the solution could be applied to. This strategy was used to transfer solutions across similar cases, but not to capture the process that was followed to generate a solution and apply it to new cases.

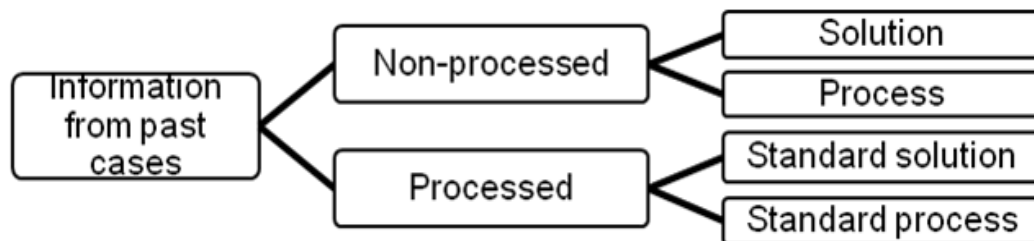


Figure 6.9 Ways to reuse information from past cases.

At the supplier of drilling equipment, processing service knowledge and generating standard solutions was not common practise. The only exception was when a severe issue on mining safety, health or environment occurred; in this case a solution applicable to a wide range of rigs was studied and all the rigs with similar equipment were informed of the issue and instructed on what to do in order to prevent its occurrence.

#### 6.3.4 Evaluation of reaction and validation

In this section the RSK model that was developed to improve the reuse of service knowledge at the supplier of drilling equipment is evaluated against the findings from the aircraft manufacturer with respect to the reaction and validation.

##### ***Reaction***

Preliminary feedback on the RSK model was received by industrial practitioners during a workshop conducted by S. Ahmed-Kristensen at the Technical University of Denmark in 2009. Consequently the model was presented to service engineers and the

industrial researcher from the aerospace company. In both the cases the audience appeared familiar with the topic and confirmed the relevance of the model also for other industries, as the interest in how to capture knowledge in a codified manner in order to facilitate its access and reuse is common across different industries.

The dialogue with the aircraft manufacturer also confirmed the importance of integrating service knowledge into existing documentation; this was turned into common practice by service engineers, who integrated the user's and maintenance manuals with experience from service.

### ***Validation of the results***

The main purpose of the auxiliary case study carried out within the aerospace industry was to verify whether the RSK model could be applicable to a different industrial context.

The analysis of the differences between oil and aerospace industries and their approach towards service showed that the aircraft manufacturer had adopted a more standardised way of handling service cases, facilitated by the characteristics of the product in question that allowed a well defined allocation of tasks within the service department, in comparison to the supplier of drilling equipment. However, despite the differences between the two companies, commonalities emerged in their interest in improving the organisation of repositories, e.g. by better understanding what information is relevant to capture and store, how it should be retrieved and which structure of the repositories would support this best.

The paragraphs to follow discuss the validity of the RSK model. The discussion is presented following the research questions described in Chapter 1, namely:

- What characterises service knowledge? What aspects of service knowledge are relevant to reuse?
- How is service knowledge transferred within service and across phases of the lifecycle?
- How can the reuse of service knowledge be facilitated?

What characterises service knowledge? What aspects of service knowledge are relevant to reuse?

Detailed investigation of the types of service knowledge relevant to be reused was not covered by the auxiliary case study as this topic has already been considered by previous research, conducted within the aerospace industry and reported in Chapter 3. Jagtap *et al.* (2008) indicated knowledge related to failures, maintenance and lifecycle is among the knowledge from service that is most valuable to reuse, hence this justifies the relevance of a model that aims to improve the management of knowledge for the aerospace industry.

How service knowledge is transferred within service and across phases of the lifecycle?

The auxiliary case study from the aircraft manufacturer focused upon the transfer of service knowledge within service, as the long development process of an aircraft impeded investigating the reuse of service knowledge during the design of the next aircraft.

Differences in how knowledge was transferred emerged from the comparison of the two cases. A systematic capture of service knowledge into documentation characterised the aircraft manufacturer, with documentation playing a central role while providing in-service support. On the contrary, the supplier of drilling equipment heavily relied on personalisation strategies for transferring knowledge, particularly when it arose from service. These differences were motivated by the characteristics of the industries taken into account and the organisational culture of the specific companies, as summarised in Table 6.4.

How can the reuse of service knowledge be facilitated?

The RSK model, that was developed based on case studies from the oil industry, has been compared to the industrial practice at the aircraft manufacturer to verify its applicability to other contexts and the results are described here.

The aircraft manufacturer has implemented a strategy based on codification for capturing service knowledge and reusing it while handling new in-service support cases. This strategy included several elements that were identified as areas of improvement from the analysis of the case from the supplier of drilling equipment and constituted central elements in the RSK model. These elements included:

- Analysing information from service cases. Recurrent cases were grouped together and standard repair methods were elicited and distributed both among service engineers and to the clients. When a standard repair method could be applied to a new case, the validation of the method was not necessary.
- Facilitating information retrieval. A single interface to access the wide range of documents generated during a service case (including internal and external emails, problem description, suggested repair method, verification of the repair executed) was under development;
- Reusing process knowledge: a standardised process for generating and validating the solution to a service case was implemented;

The comparison between the case studies from the two industries confirms that the issues that emerged from the analysis of the cases from the oil industry are relevant beyond the specific case, as they were common also to the aerospace industry. The recommendations proposed to improve the reuse of service knowledge, and summarised in the RSK model were supported by the auxiliary case study where, in many cases, these recommendations were already part of current practice.

Additionally, the comparison of the two industries depicted two contrasting approaches throughout service provision and indicated the factors that should be taken into consideration to facilitate the adoption of codification as an approach towards knowledge transfer.



## 6.4 Summary

This chapter has discussed the internal and external validity of the RSK model, which was tested against reaction and validation, in agreement with the framework proposed by Ahmed (Ahmed 2000).

The internal validity of the RSK model was tested through a workshop carried out at the supplier of drilling equipment that involved service engineers and engineering designers. The approaches suggested by the participants in order to improve the reuse of service knowledge were compatible with the proposed model.

The external validity of the findings was tested by presenting the results to industry and by conducting an auxiliary case study within the aerospace industry. The approaches towards in-service support of aerospace and oil industries diverged. The aircraft manufacturer that was investigated in the auxiliary case study provided mainly remote support based upon a rigorous workflow that included the validation of a proposed solution before its implementation and a standardised communication flow between service engineers, customer service and clients. Documentation from past cases and standard repair instructions were systematically used within service to facilitate the process. Particularly, the available documentation was reused in two different ways: (1) to transfer the process that led to the identification or to the validation of a solution; (2) to transfer a solution.

On the contrary, the supplier of drilling equipment adopted a more personalised approach that relied to a great extent on the direct communication between the client and service engineers, frequently sent on site to implement the solution. This approach relied upon the personal experience of service engineers and the support provided by senior engineers who informally validated the selected solution, and did not include a systematic reuse of documentation from past cases.

The comparison of the knowledge management strategy adopted in the aerospace industry with the RSK model indicated that many aspects suggested by the model had already been adopted at the aircraft manufacturer. Whereas issues related to information structure and retrieval (e.g. defining suitable indexing criteria and

integrating various repositories) still characterised both the industries and represented one of the main challenges to face in the future.

The RSK model, which was developed from the analysis of case studies from the oil industry, resulted in being compatible also with the aerospace industry. Particularly, a systematic analysis of available documentation from service and its translation into static knowledge (e.g. user manuals, company's procedures) would benefit both the industries.

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## 7. Discussion

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### 7.1 Introduction

This chapter discusses the research project from two perspectives: its contributions to research and its implications for industry.

First, in Section 7.2, the research project is discussed in relation to research in engineering knowledge management and the main areas of contribution are identified. Then Section 7.3 suggests the implications of the research project for industry. Finally section 7.4 discusses the limitations of the research project and proposes suggestions for future work.

### 7.2 Research contributions

The main field of contribution of this project is the engineering knowledge management field, as the objective of this field is to understand how to make knowledge available to designers and engineers in a readily usable form in order to reduce development time and cost and improve a product's quality.

More specifically, the aims of research on engineering knowledge management include:

- Understanding the capture, storage and retrieval of engineering design knowledge.
- Understanding decision making in engineering design and the nature of design expertise.
- Developing theories that can form the basis of new methods and tools.
- Developing and testing prototype methods and tools.

Engineering knowledge management adopts approaches commonly used in other research fields (e.g. information science, knowledge management, organisational science, cognitive science) to investigate the engineering design domain and conduct research projects whose findings are specifically addressed to the engineering practice.

This research project is in line with the general objectives of research in engineering knowledge management, as it investigated the dynamics that characterise the transfer of engineering knowledge generated in the later phases of a product lifecycle and proposed a model to support the reuse of this knowledge in order to improve the design of the next generation of products and the support provided during the service phase.

Most of the research studies in engineering knowledge management are focused on data and information management, and result in the proposal of new software tools. On the contrary, this research project approached engineering knowledge management from a broader perspective, investigating engineering practice with methods common to research in the social sciences, and focused upon the understanding of the needs of the engineers in relation to knowledge reuse, rather than upon the development of a software tool.

The findings of the research project have been presented to the engineering design community through various conference and journal papers; they are reported in Appendix 6. The main areas of contribution of the project are: (1) service knowledge, (2) engineering change management, and (3) a model to support the reuse of knowledge from service. These are described in the subsections to follow.

### **7.2.1 Service knowledge**

The literature survey from the engineering design domain presented in Chapter 2 stressed the importance of the behaviour of a product during the service phase, particularly when new business strategies that require the involvement of the manufacturer throughout the product's lifecycle are adopted. These strategies are motivated by the tendency of engineering companies to move towards the provision of services together with, or instead of, products, in order to differentiate themselves from the competitors.

This interest of industry in the development of services is the prime driver of research in Product-Service Systems (PSS) and service design. However the case studies taken

into consideration were not PSS, as service and maintenance still represented a source of revenue for the supplier of drilling equipment and the aircraft manufacturer.

Despite the positive effects that could derive from the reuse of knowledge from service, still little has been done to understand the knowledge needs of engineers in this new business context and a deeper understanding of the service phase and the peculiarities in relation to knowledge management is still required. This motivated the focus of this research project upon understanding how to capture and reuse knowledge arising from the service phase. The case studies from the oil industry helped identify the types of knowledge from service that are more relevant to be reused and highlighted the need for distinguishing between procedural knowledge, that is mostly relevant within the service phase, and declarative knowledge that is valuable to be reused also in the design phase. The case studies also improved the understanding of the mechanisms influencing the reuse of knowledge in the engineering domain, particularly with regard to knowledge from the service phase, and identified the main drivers and barriers for knowledge transfer within and across the phases of a product's lifecycle.

### 7.2.2 Engineering changes

The analysis of documentation on engineering changes in different industries led to the identification of the peak of the distribution of the number of changes in the later phases of a product's lifecycle and showed that the motivation for change varies depending on the phase of the lifecycle when a change occurs. Additionally the case study of changes in four similar offshore oil rigs showed that reusing knowledge from past cases helps reduce the number of changes emerging throughout a product's lifecycle.

Hence, the findings from the research project contributed to the progress in research on engineering change by determining a link between the motivation for change and the phase of the lifecycle when a change occurs and identifying the pattern of the distribution of engineering changes throughout the lifecycle of a product.

The analysis of engineering changes also provided empirical evidence supporting the hypothesis at the base of the research project: that reusing knowledge from service can enhance the quality of a product, both in terms of its design and of the in-service support provided by the manufacturer throughout the product lifecycle.

### **7.2.3 Knowledge management model for reusing service knowledge**

The prescriptive study illustrated in Chapter 5 applied general knowledge management theories and frameworks to the engineering domain. The result is the RSK model, which suggests how to manage knowledge generated during service taking into consideration the needs of the practitioners involved in the different phases of a product's lifecycle and the dimensions in which knowledge from service could be reused. The RSK model is specifically targeted to facilitate the reuse of codified knowledge, i.e. information captured in documentation, despite the analysis of the case studies suggesting that personalization strategies were the preferred way for transferring service knowledge. This choice of focusing on codification rather than personalisation was motivated by factors like the high turnover and mobility of employees, that do not allow companies to rely on employees as repositories of their knowledge.

The RSK model indicates the steps to follow to facilitate the transfer of this knowledge. The core of the model is the analysis phase, as the case studies indicated that capturing knowledge in documentation was not sufficient to ensure its reuse. A further step that focuses on the evaluation of available information in order to make it available to the targeted users in a form that matches their needs is critical for a successful reuse of information.

This represents a contribution to research on engineering knowledge management as the existing research in this field is mostly focused on the development of software tools to facilitate the reuse of information, but it does not clearly define the context in which these tools should be applied and for which purpose.

### **7.3 Implication for industry**

The analysis of documentation on engineering changes showed that the reuse of knowledge results in a reduction of engineering changes arising throughout a product lifecycle. Hence industry could greatly benefit from a better reuse of service knowledge. The RSK model, developed based on the findings from the case studies, can be directly applied to companies with similar characteristics and used when designing a knowledge management strategy targeted to improving the reuse of knowledge generated during the service phase. Besides the RSK model, the framework for the development of a knowledge management strategy derived from Kamara's framework, which has been described in Chapter 5, can be used to evaluate whether the conditions that led to the development of the RSK are verified in a different industrial context. If this is not the case, the proposed framework can be used as support to develop a knowledge management strategy that is suitable for the specific industry.

The evaluation of the industrial context through the proposed framework would also push a company to define the objectives that should be achieved with the implementation of the knowledge management strategy before selecting a (software) tool, hence avoiding the adoption of a tool that is not able to answer the need of the business.

### **7.4 Limitations**

This section discusses the limitations related to each phase of the research project.

#### ***Case selection***

The main case studies were conducted within the oil industry. This choice gave depth to the analysis of industrial practice; however it represented an issue with regard to the external validity of the findings. The author tried to overcome this issue by comparing these cases to one from the aerospace domain (see Chapter 6).

Moreover, the choice of specifically focusing on complex, customised products impacted the way the collaborating companies were involved in the service phase, i.e.

mainly providing installation support, repairs, maintenance and spare parts, and consequently the type of knowledge generated during service.

In a different industrial context, e.g. that of mass consumer products, the benefits from reusing knowledge from the later phases of a product's lifecycle may differ from those identified in this thesis, and be more related to achieving a better understanding of the customers and the market than to improving performances of the products.

### ***Methods***

The case studies were investigated through semi-structure interviews, a survey and document analysis. Hence all the data were collected retrospectively and biased by the personal perception of the participants to the interviews and the survey and the point of view of people who created the documentation. Completing the case studies with the analysis of other types of empirical evidence, e.g. observations, would have benefitted the research project, however several factors posed a barrier to the collection of this type of data, including:

- Some of the events analysed, e.g. changes, could not be predicted in advance;
- The complexity of the drilling equipment required multiple design teams; the development process was difficult to be followed by a single external observer without in-depth knowledge of the product in question.
- The researcher was not able to understand the mother language of most of the employees working at the collaborating company. Asking them to complete their daily task in English would have influenced the quality of the data collected through observation and protocol analysis.

For the above reasons the data were solely collected through retrospective methods.



### ***Assumptions***

The RSK model was developed based on the assumption that information overload needed to be avoided, and this objective was achieved during the analysis phase, when available information was processed in order to facilitate its reuse. However the continuous progress of Information Technology might make this phase unnecessary in the future, as new ways of searching for information, e.g. semantic search, are developed. Once new technology is mature enough to be deployed in industry, the processing of information could occur after information has been requested – hence without the need for deciding in advance how information is reused.

### ***Validation of the results***

The RSK model that was developed in the prescriptive study has not been implemented in industry, due to time limitations and difficulties in influencing a company's knowledge management strategy (e.g. software licences, structure of the databases, organisational strategies). The guidelines specifically addressed to the company representing the main case study had not been implemented at the company when this thesis was written.

Due to the impossibility of influencing industrial practice within the timeframe of the project, an alternative way of validating the results was adopted. The results from the case study from the oil industry were first presented to practitioners from industry, in order to receive their feedback, and then compared to the practice characterising the aerospace industry.

## **7.5 Summary**

This chapter discussed the implications of the research project for academia and industry.

First the contribution of the research project to research on engineering knowledge management has been discussed. Three specific areas of contribution within this field have been identified, namely service knowledge, engineering changes, and the development of a knowledge management model suitable for the engineering domain.

Subsequently, the implications for industry have been presented. Finally, the limitations related to the methods adopted to conduct the research project have been discussed.

## 8. Conclusions

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This chapter provides a summary of the research project and a description of the main areas of contribution. Suggestions for further research are also presented.

### 8.1 Motivation of the project

The research project presented in this thesis is based on the paradigm that we are now living in a knowledge economy, where knowledge is used to produce economic benefits as well as job creation. In this context, knowledge resources such as know-how and expertise are considered as critical as other economic resources.

This project was motivated by the need to improve the reuse of the technical knowledge available within a company in order to improve the overall quality of a product, specifically when this knowledge is generated in the later phases of a product's lifecycle. It was conducted in collaboration with a company supplying drilling systems for the oil industry. The collaborating company was involved throughout the entire lifecycle of the equipment: from developing a concept to supporting the operators during the service phase (e.g. providing maintenance, repair, training, overhaul, spare parts, upgrades); however the knowledge generated during the later phases of the lifecycle of the equipment was not systematically taken into consideration during the design phase

Three research questions were identified and have been answered through case studies.

- RQ.1 *What characterises the knowledge generated during the service phase of complex products? What aspects of knowledge from service are relevant for service engineers and engineering designers?*
- RQ.2 *How is knowledge from service transferred within the service phase and across phases of the lifecycle?*
- RQ.3 *How can the current situation be improved in order to obtain a systematic reuse of knowledge from the service phase of complex products?*

## 8.2 Answers to the research questions

The purpose of the first research question is to better define the characteristics of knowledge generated during the service phase and understand how service engineers and engineering designers perceived it. The case studies suggested that the type of knowledge generated during service that was more relevant for both service engineers and engineering designers was knowledge about *changes, issues and improvements*; other relevant types of knowledge were knowledge about *product* and *project*. Particularly important beyond the specific cases taken into consideration is the distinction between procedural and declarative knowledge, as the first is valuable only within the service phase, whilst the latter is of interest across the different phases of a product's lifecycle.

The second research question is meant to investigate the knowledge transfer mechanisms that are adopted for transferring knowledge within service and across the phases of the product's lifecycle. The analysis of the case studies showed the lack of a systematic reuse of knowledge from service and indicated that, despite the implementation of knowledge management strategies based on codification, knowledge transfer still heavily relied on personalisation. When knowledge transfer occurred across phases of a product's lifecycle, it was driven by service engineers that actively made information available to engineering designers, whereas the engineering designers tended not to search for information from service during the design of a new product. The presence of a senior employee who acted as knowledge broker was necessary in order to point to the information from past cases that may be relevant in a specific context.

The main barriers for the reuse of service knowledge that emerged from the case studies were addressed whilst developing the model for managing service knowledge (the RSK model) that represented the answer to the third research question. The model describes how to achieve a systematic reuse of the knowledge about changes, issues and improvements that is generated during the service phase of a product. It identified two dimensions in which this knowledge can be reused:

- During the development phase, in order to improve the design of the next generation of products by avoiding the repetition of issues already detected in previous products and evaluating suggestions for improvement.
- During the service phase, in order to provide faster and more consistent service interventions.

Both procedural and declarative knowledge are relevant to be transferred within the service phase, whereas only declarative knowledge is valuable for engineering designers.

The RSK model includes an “analysis” step that precedes the retrieval and reuse of documentation, as integrating knowledge from new service cases into existing documentation facilitates its systematic reuse and helps avoid information overload. This step leads to the distinction between processed information (after analysis) and non-processed information (before analysis).

*Non-processed information:* includes all the information strictly related to a specific case that has been generated in order to answer specific needs, e.g. service-requests, spare part orders, service reports, repair methods. This type of information is hard to be reused by users without prior awareness of the nature of the case.

*Processed information:* refers to information that is the result of the analysis of documents or practices. This type of information is easier to transfer to new cases as:

- The context in which it can be relevant (e.g. type and severity of damages to which a solution could be applied) is clearly described;
- It is explicitly generated to be reused across cases; hence it includes only valuable information;
- It represents a trustworthy source;
- The number of “processed” documents is limited compared to those capturing non-processed information.

The RSK model is meant to be applicable beyond the specific case investigated through the case studies, as its purpose is to facilitate the reuse of knowledge about

*changes, issues and improvements*, which has been proved to be of general relevance for the engineering domain.

First the internal validity of the RSK model was investigated through a workshop carried out at the supplier of drilling equipment and the feedback received was positive. Then the external validity of the RSK model was tested by presenting it to industry and by conducting an auxiliary case study within the aerospace industry. The comparison between the knowledge management strategy adopted in the aerospace industry and the RSK model indicated that many aspects suggested by the model had already been adopted at the aircraft manufacturer. Whereas issues related to information structure and retrieval (e.g. defining suitable indexing criteria and integrating various repositories) still characterised both the industries and represented one of the main challenges to face in the future.

### **8.3 Contributions**

This project contributed to the progress of research in the field of engineering knowledge management and had direct implications for industry.

#### **8.3.1 Contribution to research**

Three specific areas of contribution within the field of engineering knowledge management have been identified, namely: (1) service knowledge and its transfer, (2) engineering change management and (3) the development of a knowledge management model targeted to the engineering domain.

##### ***Service knowledge and its transfer***

This project focused upon knowledge generated during the service phase of a complex product and how it was transferred and eventually reused. The analysis of the case studies highlighted the tendency of engineering designers not to actively search for information from service, and expecting relevant information to be pushed to them when needed. It also identified knowledge about *changes, issues and improvement* as the type of knowledge from service that is more relevant to be reused.

The findings are relevant for other research projects that aim to increase the value of a product throughout its lifecycle (e.g. research on product service systems) as they suggest which are the types of knowledge generated during service that need to be taken into consideration in the design phase in order to improve a product's behaviour in service.

The finding that procedural and declarative knowledge need to be treated differently, as the first is relevant only in the context in which it has been generated whilst the latter is of more general interest, has direct implications on how these types of knowledge need to be handled and on the structure of the documentation in which they are captured. Procedural knowledge that was generated during a service case should be reused within the service phase in order to achieve more consistent troubleshooting and the development of best practices widespread at organisational level. Declarative knowledge from service can be used to support both service engineers, as during a service intervention they may adopt solutions already implemented in previous cases, and engineering designers, as they are made aware of issues that need to be addressed during the development of the subsequent generation of products.

### ***Engineering change management***

The analysis of changes arising throughout the lifecycle of a product indicated that changes during the design phase were driven by product improvement whilst changes during installation and service were mostly motivated by the need for correcting design faults. Furthermore, installation and service were the phases of the product lifecycle with the highest number of change requests. These findings suggest that engineering designers are not fully aware of the issues characterising the later phases of a product's lifecycle and confirm the importance of improving their understanding of the lifecycle of a product in order to avoid costly changes to the product after the design phases are concluded. This represents a further justification of the research project presented in this thesis.

### ***Knowledge management model for engineering***

The RSK model presented in the prescriptive study was developed to overcome the main issues identified through the case studies. This model represents a different way of proposing a solution to knowledge management issues, if compared to the approaches commonly adopted in the engineering domain, as existing research tended to develop new software applications instead of focusing on the needs of the users.

The main contribution of the RSK model to the progress of research in the engineering knowledge management field is linked to the integration of the standard knowledge lifecycle, which is based on the capture-retrieve-reuse phases, with an analysis phase that precedes the retrieval of knowledge.

The analysis phase helps to avoid information overload and facilitates the retrieval of information by presenting it in a way that meets the needs of targeted users. Analysing information that may be scattered in different repositories and using it to update existing documentation has also a positive effect on the users' trust in it.

#### **8.3.2 Implication for industry**

The RSK model provides support for companies aiming to develop a knowledge management strategy that facilitates the reuse of the knowledge generated during the later phases of a product's lifecycle. As the process that was followed to build the model has been described in detail, a company could compare the issues that triggered the development of the RSK model with its specific conditions and assess whether the proposed model would be able to answer its needs.

### **8.4 Further work**

Further empirical research from case studies outside the oil industry would strengthen the findings of the research project. Particularly, investigating the characteristics of service knowledge and how it is transferred in a different context would be useful to verify the general validity of the findings. Additionally, implementing the RSK model to industry and evaluating its effect would provide further validation of the model



itself. Unfortunately the application of the RSK model to industry was not possible within the timeframe of the project.

## A.1 - Survey

**1. Which type of information do you store for public use (on databases, E-net, public folders)?**

Email

## Procedures

## Project documentation

## Calculations

## Drawings

Service interventions or service orders

## Construction change notification – CCN

## Non conformance reports – NCR

## Alerts

## Other technical reports

Other: ...

[illegible]

## 2. Where do you store information for public use?

MySAP

SAP

WOSS

SPS

## Frames

CCN

MIPS

## Public folders

E-net

Other: ...

[illegible]

### 3. Which type of information do you retrieve from databases, the E-net or public folders?

Email  
 Procedures  
 Project documentation  
 Calculations  
 Drawings  
 Service interventions or service orders  
 Construction change notification – CCN  
 Non conformance reports – NCR  
 Alerts  
 Other technical reports  
 Other: ...


### 4. Where do you retrieve information from?

MySAP  
 SAP  
 WOSS  
 SPS  
 Frames  
 CCN  
 MIPS  
 Public folders  
 E-net  
 Other: ...


### 5. Which type of information do you seek?

Information about products  
 Information about processes or procedures  
 Information about functions (what a product does)  
 Information about issues or past errors  
 I don't know


**6. How often do you store information for public use (on databases, E-net or public folders)?**

Several times a day  
 Weekly  
 Monthly  
 A few times a year  
 Never


**7. How often do you retrieve information from databases, E-net or public folders?**

Several times a day  
 Weekly  
 Monthly  
 A few times a year  
 Never


**8. Why do you seek the information on databases, E-net or public folders?**

Because I know what I am looking for  
 Because nobody can answer my question  
 Because I don't want to disturb my colleagues  
 Because it's the right place where to find the information I need  
 Other: ...


**9. How often do you find what you are searching for?**

Always  
 Often  
 Sometimes  
 Rarely  
 Never


**10. How much time do you spend seeking the information on E-net, databases or public folders during a week?**

I never seek the information on E-net, databases or public folders  
 Less than 5 hours a week  
 5 to 10 hours a week  
 10 to 15 hours a week  
 More than 15 hours a week


**11. Which search criteria do you use when seeking the information?**

- Product
- Project
- Rig
- Document number
- Tag number
- Division
- Case Number
- Employee number
- Date of initiation
- Date of conclusion
- Date of action
- Case status
- Product status
- Location
- Case type
- Phase
- Type of equipment (system)
- Control system and node
- Part number
- Other: ...


**12. Are there any other search criteria you would like to use?**

## A.2 - Example of collected data and their analysis through the coding scheme.

---

### **Examples of instances for each of the types of knowledge used in the coding scheme**

#### ***Product***

“On almost every project, we need to come up with something specific. Of course, we can base most of the delivery on earlier projects, earlier deliveries, but very often we need to come up with something new at least. Because, no rig is identical, and no client is identical either.”

“During a service intervention I don't have the drawings with me because we can get them via internet () so we can go in and see and get the drawings(). Design specifications and functional specifications and all the information that is made during the project is available. I'm not sure where.”

#### ***Process and procedures***

“MIPS is a project execution programme, it takes care of all. So you can do the installation and commissioning job according to procedures and drawings and all the documents are connected in there.”

“I see as a problem that there is a belief that if you place a new procedure in the intranet, it will be implemented. In this way you fail. That is the truth, and will always be the truth because you need to supervise the implementation.”

#### ***Project***

“We also have problem now, or not a problem, but we are a kind of doing commissioning while we are still in engineering because we are so busy. Several of

our equipment has not been tested as it should be, in our test towers. We have send it away before, because of political reasons, and installation reasons, so we are not totally tested, or maybe it is tested, but didn't work as it should."

"When it goes to operation, I think it is \*\*\*\*\*rig database is the name, where they store the experiences from one project to another."

### ***People and organisation***

"It is more organisational issues, who is responsible for what, and how do you do this. So for the product, I have myself been asking questions. I am working with quality, and the customer decides the quality, so I think it is very important to get the information from the people that are out with the customers all the time, how are the machines working, and getting this back into the designers, but I really don't see how it happens, I'm not sure if it happens, or if it is very, happens sometimes, I don't think that there are any structure on how this information gets back."

"Knowing my people, their capabilities and where to put the task, if there is a task, handling them as effectively as I can. That is definitely the most important part of my job."

### ***Operation, lifecycle and service***

"It is matter of improving the quality of the documentation. I don't think we have some external requirements but we ourselves see that we need more control on the documentation, to be able to handle all the rigs we have in operation. So, because, a rig is not just a project, you know, for 18 to 24 months it is also the operation time which is 20 to 30 years, with upgrading and follow up work and so on, so it really important for us to have the control with the documentation, on the issues we are solving, at least."

“There is no formal agreement with the drilling contractors, we cannot force them to feedback information about how the machines work, but we know, it is natural, if there is something they don’t like, they will come back immediately.”

### ***Domain***

“The drilling industry, the oil industry, is an international business, where communication is quite easy, because it got its own culture but when we are working towards the yards, we have a lot of local culture that you have to pay attention to. How do they do business in Singapore? How do they control their projects in Singapore? And the same in Korea of course. And also in China. So we have a culture challenge as well.”

“It is important the theoretical part, but I have seen that my practical knowledge is also very very valuable.”

### ***Function***

“The most important thing is to know what the equipment should do. That is the most important. And after that, you start to looking into design of the different part of the equipment and sizing them.”

### ***Changes, issues and improvements***

“We have a database called CCN system so if we have some problems, changes in some of the equipment after the Factory Acceptance Test then we make a CCN to write down what is the problem, whether is it specific for this equipment for this rig or it is maybe in 3 rigs 4 rigs.”

“the lessons learned is collected. You have a meeting and everyone is allowed to tell whatever they feel, without anyone to stop them. It is like a Risk analysis. And it is noted down and you end up with a list, with maybe 20 points, this is important for us to not do again, or maybe the other way, it is important to do again because it might be positive. It is a good lesson learnt. And then it is collected, and made to available to all.”



**Example of how the coding scheme was applied to analyse the interviews**

		Missing	Wanted	Object	Type of capture	Initiation: sender	Initiation: receiver	Mechanism
Q	Do you receive reports of service interventions?							
A	No I would say not, but they ARE available. Eehm, there are some SPS sites, that we can jump into, and try to find out. But we don't do that.	True		Operation, lifecycle and service	Codified	Operation	Equipment	Pull
A	Where we have problems, we might do that directly ourselves, but we usually go through service, senior service. The senior service group, if we need to have some experience transfer, from a special rig.			Changes, issues and improv.	Personal	Operation	Equipment	Pull
Q	When does the senior service group contact you?							
A	If they have a problem that they either don't have resources for handling or technical experience, or if they sort of getting into design issues, then they contact us			Changes, issues and improv.	Personal	Equipment	Operation	Pull

## A.3 - Validation of data analysis

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This Appendix describes the methods used to validate the results from the data analysis.

### **Quantitative data**

Two types of statistical analysis were applied to validate the quantitative analysis of the data.

#### *Chi squared*

A chi squared test was applied to assess similarities between distributions, i.e. whether distributions of the number of documents arising throughout the lifecycle of different projects were similar.

The chi-square test is a statistical method that can be applied to testing whether the similarities between two (or more) distributions are statistically significant; it examines whether two populations have the same proportion of occurrences with a common characteristic through the formula:

$$X^2 = \sum_{i=1}^n \frac{(O_i - E_i)^2}{E_i},$$

Where:

$X^2$  = the chi-square statistic.

$O_i$  = an observed value;

$E_i$  = an expected value (e.g. a value expected when the null hypothesis, of no difference between the two categories is true) ;

$n$  = the number of possible outcomes of each event.

The chi-square statistic is compared to a theoretical chi-square distribution in order to calculate a probability value (p-value) that represents the probability of error associated with rejecting the hypothesis of no difference between the two categories of observations.

When p-value is <0,05 the distributions have statistically significant similarities.

### *Cohen Kappa*

The Cohen kappa ( $\kappa$ ) evaluates the reliability and replicability of a coding scheme. It assesses the influence of the personal perception of the coder on the way the coding scheme was applied to the available data by measuring the agreement between two coders (whilst considering the probability of a chance agreement), who each classify  $N$  items into  $C$  mutually exclusive categories. The equation for  $\kappa$  is:

$$\kappa = \frac{\text{Pr}(a) - \text{Pr}(e)}{1 - \text{Pr}(e)},$$

where  $\text{Pr}(a)$  is the relative observed agreement among raters, and  $\text{Pr}(e)$  is the hypothetical probability of chance agreement.

If the coders are in complete agreement then  $\kappa = 1$ . If there is no agreement among the coders (other than what would be expected by chance), then  $\kappa \leq 0$ . Landis and Koch (Landis and Koch 1977) suggested a scale, reported in Table 2.4, for interpreting intermediate values of  $\kappa$ .

Table A3.1 Interpretation of the value of the Cohen's Kappa

$K$	<i>Interpretation</i>
< 0	No agreement
0.0 — 0.20	Slight agreement
0.21 — 0.40	Fair agreement
0.41 — 0.60	Moderate agreement
0.61 — 0.80	Substantial agreement
0.81 — 1.00	Almost perfect agreement

### **Qualitative data**

Validation is also an issue when dealing with qualitative data, e.g. derived from open-ended and semi structured interviews.

The internal validity of the results from a case study can be verified by using multiple sources of evidence and proving the convergence of findings from different lines of inquiry in a process of triangulation of data (Yin 1994). In the case of the research illustrated in this thesis, triangulation was achieved by comparing the insights gained through interviews with available documentation.

The external validity of the results of a case study can be verified by comparing the results to existing literature or other case studies, identifying similarities and explaining any differences (Eisenhardt 1989).

### ***References***

- LANDIS, J.R. and KOCH, G.G., 1977. The measurement of observer agreement for categorical data. *Biometrics*, 33(1), pp. 159-174.
- YIN, R.K., 1994. *Case study research: design and methods*. 2 edn. Thousand Oaks, California: Sage Publication.
- EISENHARDT, K.M., 1989. Building Theories from Case Study Research. *Academy of Management Review*, 14(4), pp. 532-550.

## A.4 - Guidelines for the supplier of drilling equipment

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The RSK model that was developed based on the analysis of the case studies was adapted to the characteristics and the needs of the supplier of drilling equipment and resulted in the guidelines for improving the reuse of knowledge from service that are reported in this Appendix.

### **Guidelines presented to the supplier of drilling equipment**

The analysis of the management of knowledge from service showed that service knowledge was captured in documentation and stored in one of the knowledge repositories available at the company, while no standard procedure described how to reuse this information.

The benefits that the company could achieve through systematic reuse information from service included:

- Faster diagnosis, by supplying service engineers with information about similar cases, both in the form of the solution adopted and the trouble-shooting process that had been followed.
- Product improvement, by eliciting recurrent issues from service and addressing them during the design of the next generation of equipment.

The analysis of the interviews suggested that knowledge about changes, issues and improvements was relevant for both service engineers and engineering designers. However, in order to systematically transfer and reuse it through codification strategies, the company needed to:

- Achieve uniformity in documentation from different projects;
- Facilitate the retrieval process;
- Modify both content and structure of documentation, taking into account the needs of engineering designers.

Specifically, documentation needed to:

- Be concise and reliable;
- Be well structured;
- Be retrievable both at system and at component level;
- Include the cause of the problem (or at least a tentative cause) and indications of the process followed during trouble-shooting.

Additionally, the complexity of the structure of knowledge repositories was a barrier to the retrieval of information. For this reason the retrieval was often supported by a knowledge broker, an experienced employee (e.g. senior service engineer, product responsible) who was able to point out the information of relevance for a specific case. A better organisation of the knowledge repositories could facilitate the retrieval and reduce the need for a broker.

The actions to perform in order to facilitate the reuse of information from service (in accordance with the model presented in Chapter 5) include:

- Integrating current documentation with auxiliary information, describing the issue and indicating (or suggesting) the cause;
- Linking the information to the component involved;
- Integrating the review of issues from service into the product development process, e.g. by including it in the company's procedures;
- Adopting a standard way to classify issues; hence making possible, when a new issue arises, to evaluate whether a similar issue had already occurred. If this is the case, documentation on similar issues can be used as support during the trouble-shooting process.

Improving the knowledge management system does not guarantee that the relevant information from service is taken into account while developing a new product. Organisational changes should also be implemented in order to support this process. For instance, the competences of organisational units dedicated to the assessment of issues from service, such as the product improvement board and the change board, should include tasks like the evaluation of recurrent, moderate issues, and identify the directions for product improvement at organisational level.

Short term actions to improve the reuse of service knowledge were suggested at the company and are hereby listed. The dialogue with managers, engineering designers and service engineers suggested that the structure of technical reports was the first element that needed to be changed in order to improve the reuse of information from the service phase. The reasons leading to this decision include:

- The company was interested in improving the reuse of service knowledge through codified strategies, hence the focus on documentation.
- A new structure of technical reports was already seen as one of the main areas of improvement at the company, particularly in the service department.
- Information about issues arising during service was the main type of information relevant for both service engineers and designers. As the technical report was the document dedicated to capturing issues arising during service, it became natural to think of this document when aiming to improve the reuse of knowledge from service.
- Technical reports were unstructured, hence easier to modify without intervening on the structure of a knowledge repository.
- Technical reports were not subjected to external regulations that limit the possibility of implementing changes.

The approach adopted to improve the handling of information from service was based on the idea that the implementation of a single document that follows the progression of a case, from initiation to closure, was necessary in order to facilitate the retrieval of information from service. The proposed document was integrated into the workflow characterising the in-service support, and designed taking into consideration the company context and the elements that were already available in other documents. In this way the users were expected to be familiar with the information required when filling out the form and the training required was expected to be limited.

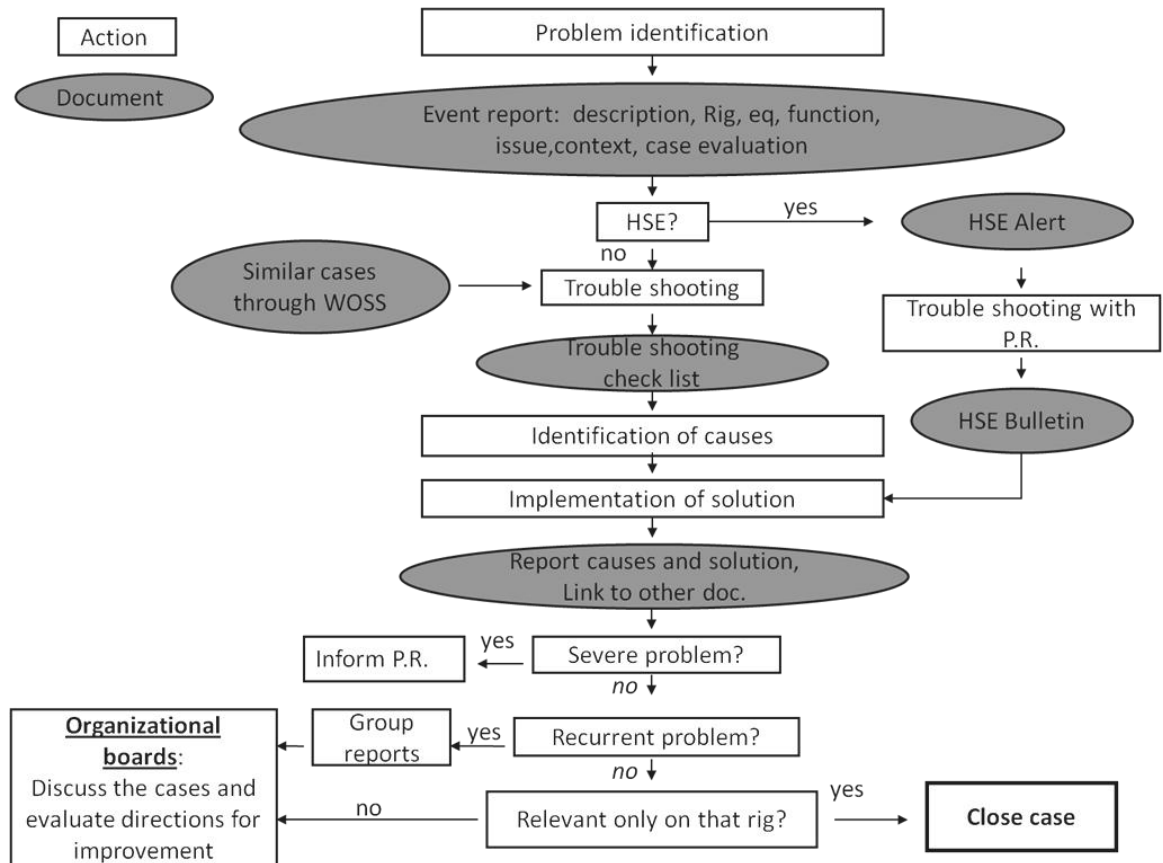


Figure A4.1 Workflow for a service intervention and documentation generated

Figure A4.1 illustrates the generation of the document reporting a service case in relation to the workflow describing the in-service support provided. The proposed document is composed of four distinct parts, that reflect the phases of the workflow:

- Problem description
- Trouble-shooting
- Identification of causes and solution
- Follow up

Below the four parts of the document are described in relation to the workflow for providing in-service support.



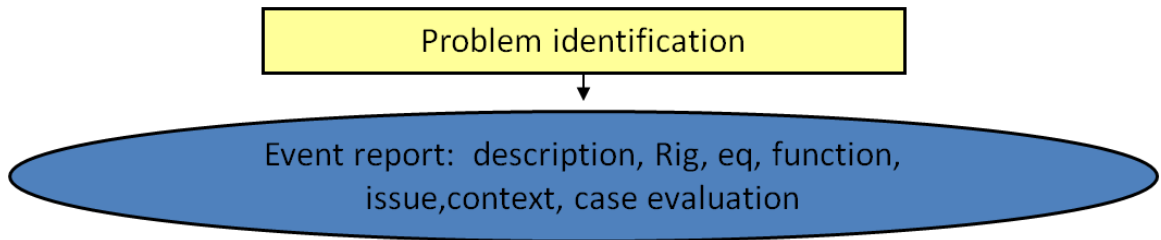
**Problem description**

Figure A4.2 First stage of the in-service support: identify the problem.

The first part of the document is dedicated to a description of the case to solve; this description could be obtained from the event report, which was already available from SAP (see Figure A4.2). However the level of detail of the event report was dependent on the member of the customer support centre completing it and the information provided by the initiator of the case, hence guidelines describing the wanted standard for describing a case should be developed. In order to facilitate searching through the available documentation in the case of future retrieval the free text describing the case needs to be integrated with a set of metadata. These structured fields should include:

- Type of case (e.g. maintenance, spare part, training) and level of support (e.g. remote, on-site). These fields had already been implemented in SAP; the type of support and the four lines of support used to describe a case in SAP could be also used to index technical reports;
- Functions involved. A taxonomy of functions could be derived from the description of standard functions already developed at the company but not implemented in any type of documentation;
- Equipment involved, defined at different levels: system, product and component;
- Discipline involved, for instance hydraulic, mechanical, electrical;
- Phase of the lifecycle, according to the company's model for developing projects;
- Motivation for service: fault correction, product improvement, carry-over work, etc.

- Issue involved, a taxonomy of issues could be developed from the list of failure modes that the company had already developed for certain standard components;
- Priority and severity of the case.

Metadata already in use in other repositories have been suggested to index the report in order to make it easier for the company to use the new document.

Additionally a case responsible, in charge of following up the case, should be determined; his tasks should embrace:

- Verifying if similar cases have already happened;
- Checking documentation is followed up according to company procedures;
- Checking progression of the case;
- Coordinating client, service engineers and product responsible.

### ***Trouble-shooting***

The supplier of drilling equipment had two different processes for handling a service case, depending on whether the case involved a Health, Safety of Environment (HSE) or not. The workflow in the two HSE cases needed to be handled in accordance with the industry's regulation and standard documentation had to be generated. On the contrary the company had the freedom to determine the processes to follow when handling cases that did not involve HSE; these cases are the focus of the analysis.

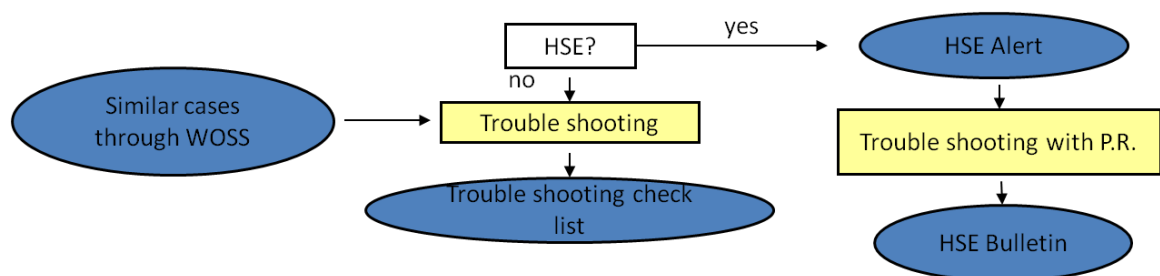


Figure A4.3 Second stage of the in-service support: trouble-shooting.

The description of the trouble-shooting process that was followed to investigate the case should be captured in a schematic form, e.g. as a checklist, easy to be applied to

different contexts. The description should include suggestions about the cause of the issue and explicit indication of the assumption made during trouble-shooting.

First the case to handle needs to be compared to previous cases. The description of the trouble-shooting process of compatible cases can be used as the starting point for the definition of the job description in the case in question. The process is consequently captured in the service documentation as a new, revised check list.

The systematic access to past cases would, in the long term, result in:

- The definition of standard, codified trouble-shooting practices;
- The reduction of the involvement of the product responsible to support service interventions.

### ***Causes and solution***

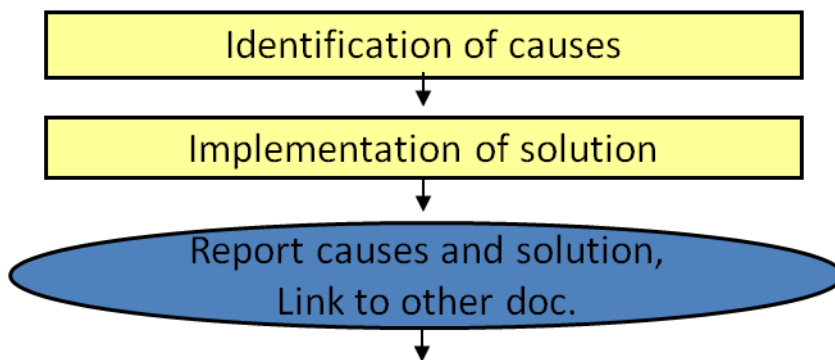


Figure A4.4 Third stage of the in-service support: identify cause and implement solution.

No systematic investigation of causes was carried out at the company at the time of the research project. However the integration of the report with tentative root causes and an explicit description of the assumption made could suggest to engineering designers the direction to follow in order to address similar problems while developing new products.

The suggested cause could be presented to engineering designers for validation, if needed. This process would help: 1) make engineering designers aware of the

problems arising from service, 2) validate available information and increase the users' trust in documentation.

The service documentation should include, together with the description of the causes, also a description of the adopted solution and the rationale motivating it (e.g. time and cost constraints). When multiple types of documentation are generated, such as product bulletins, change request or revised drawings, the supplementary documentation has to be linked to the report. This practice will provide a complete overview of a case through a single interface.

### ***Follow up***

The approach to adopt to follow up a case should be explicitly evaluated before its closure and a person responsible for it assigned. The workflow for the follow up phase is illustrated in Figure A4.5. The principal questions to answer when defining how to follow up a case are:

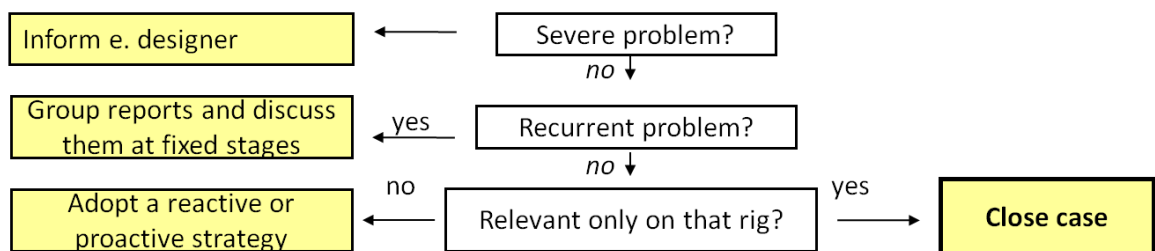


Figure A4.5 Fourth stage of the in-service support: follow up.

- “How should the information from the case be treated?”

A case should be followed up immediately as it arises or together with other similar cases, depending on whether the case deals with a severe or a minor recurrent issue

Dedicated units within the organisation should be set up to systematically follow up service cases and evaluate issues relevant across projects or of interest for the development of future products.

- “In which context could it be relevant to reuse the information arisen from this case?”

The information from a service case could be relevant solely for the rig in question, for future rigs or for other rigs in operation. The answer to this question affects the


hypothetical users of the information and the way the information should be handled. According to the descriptive study, service engineers actively search for information from past service cases when providing in-service support, while engineering designers reuse information from service only if they have been made aware of it, i.e. the information has been pushed to them.

***Comments on the guidelines for the supplier of drilling equipment***

These guidelines show an example of how the proposed framework could be used in an industrial context in order to develop a knowledge management system that takes into consideration the needs of the users. The proposed guidelines have yet to be implemented at the company at the moment of writing, so no feedback on their validity was available. The limitations of the research project are described in more detail in the following section.


## A.5 - Slides from the brainstorming session

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# Workshop on Reuse of Service Knowledge


Giovanna Vianello, Saeema Ahmed  
Kristiansand, July 1<sup>st</sup> 2009




engineering knowledge management group

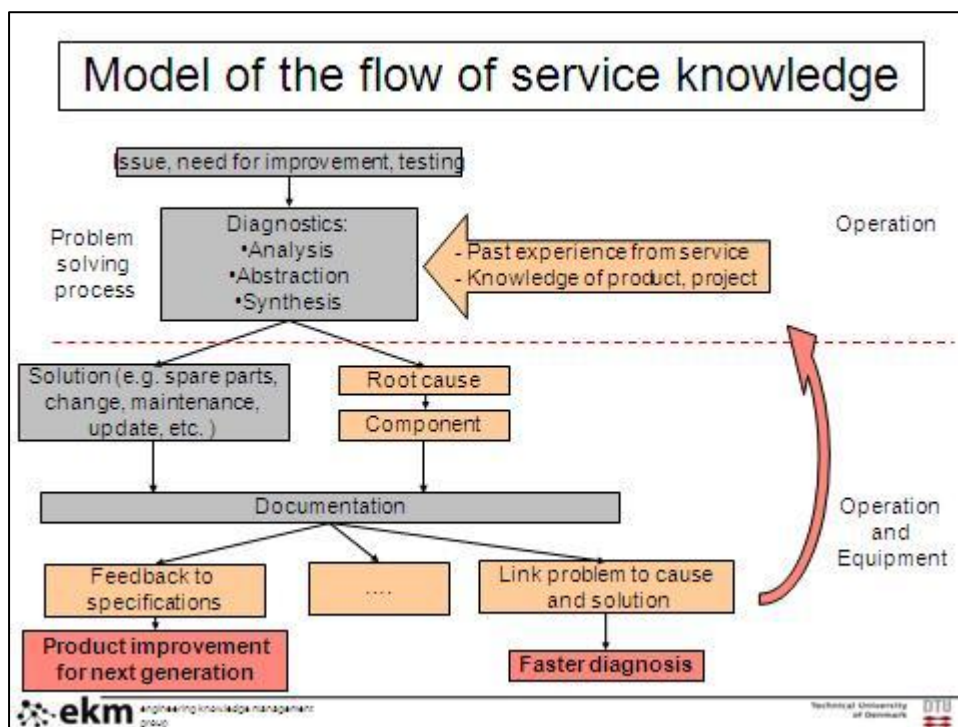
## Agenda

- Introduction to the Ph.D. project
- Discussion about reuse of knowledge from service
  - Brainstorming
  - Suggestions on documentation content and structure
- Lunch*
- Summary and evaluation of ideas from the discussion
- Future implementation and other projects



engineering knowledge management group

Technical University of Denmark 





## Desired knowledge to be transferred between Equipment and Operation

Failure during operation in high stressed components

- Roughneck

Operating conditions (temperature, environment, wear)

- Lubrication
- Performances throughout lifecycle (long connection time when system for centralizing the piping is worn)
- Dismantle and disassembly

Other areas

- Interfaces between rig structure and equipment
- Sensors and actuators, piston positioning

Up-to-date documentation during installation and commissioning

**CASE: Azeri RIP, initiated after client's complains**

## Improving reuse of service knowledge within operation department

- Handover: limited information on what has been done, remaining issues, outstanding items, contact persons
- Limited job description before leaving for a service task
- Lack of experienced people: longer commissioning times ( failed experience transfer between Maersk rigs due to day and night shifts)



## How might we....?

### Aim

Understanding how the information flow could be organised without the limitations due to the current knowledge management system

## How might we....?

- Explanatory example
- A scenario from drilling equipment is presented
- Ideal system with all knowledge potentially available
- Do not limit yourself to existing systems or communication practises at MH



## Scenario from drilling equipment

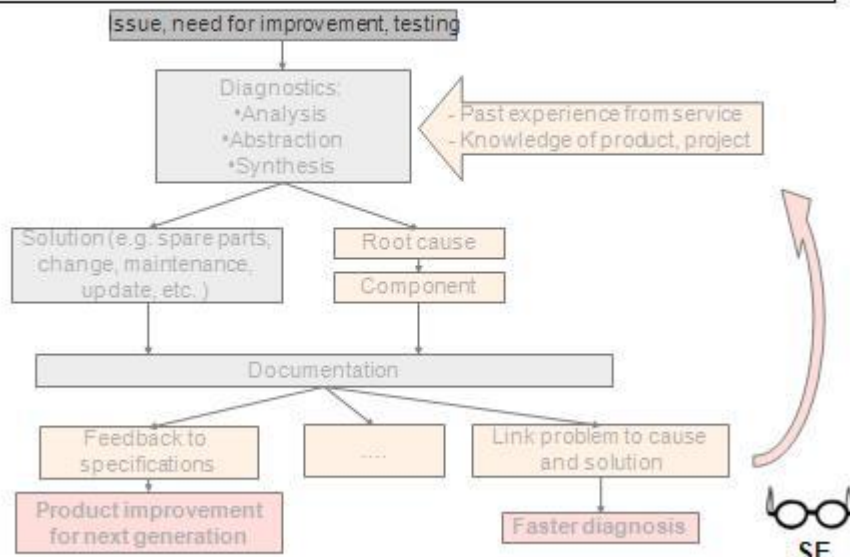
### RULES

- Questions are asked in relation to the case
- 1 minute to think about each question and talk with your neighbour.
- Plenum session: don't talk at the same time

**Remember to wear the right glasses!**  
(SE: service engineer;  
D: designer)



## Initiation of a service intervention

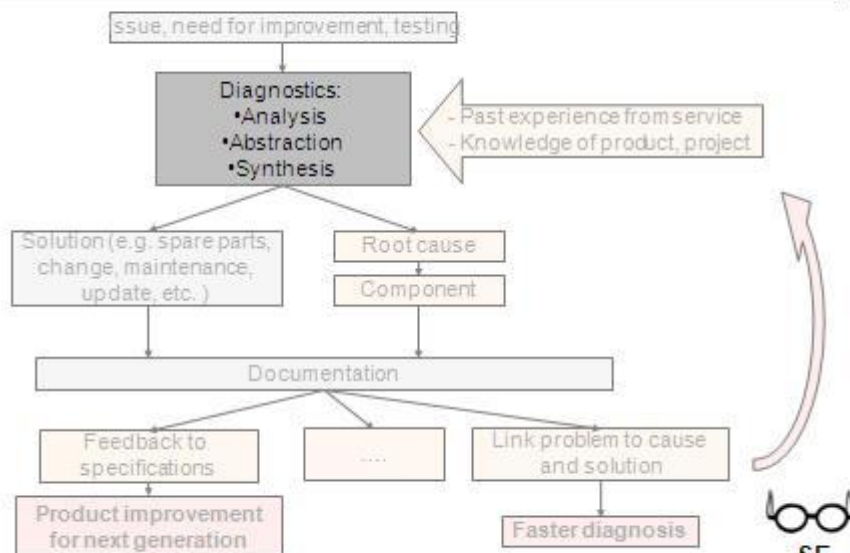


## Issue

- The equipment is in stand-by due to deviation of the hoisting beyond the acceptable limit.



## We are about to diagnose the problem



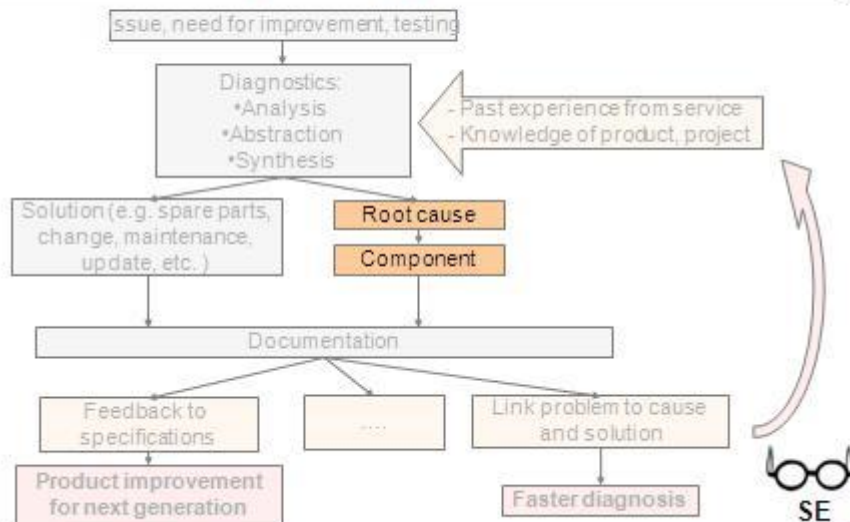
## From the sensors, the actual position differs from what expected

How might we verify whether this failure has already occurred and what was done?

- Where might we obtain this information?
- How might we use this information?



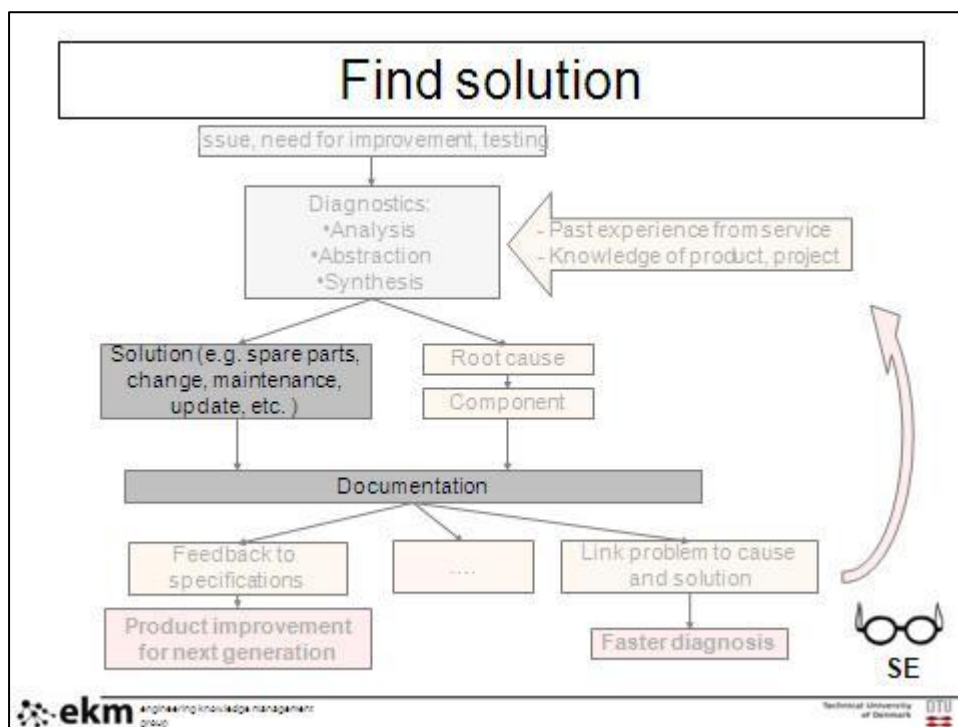
## We are investigating causes based on past experience



From previous reports we find that several movable elements have problems while in operation due to external factors that increase friction

How might we investigate the cause of the failure?

- What would it be important to know?
- Who should be involved?



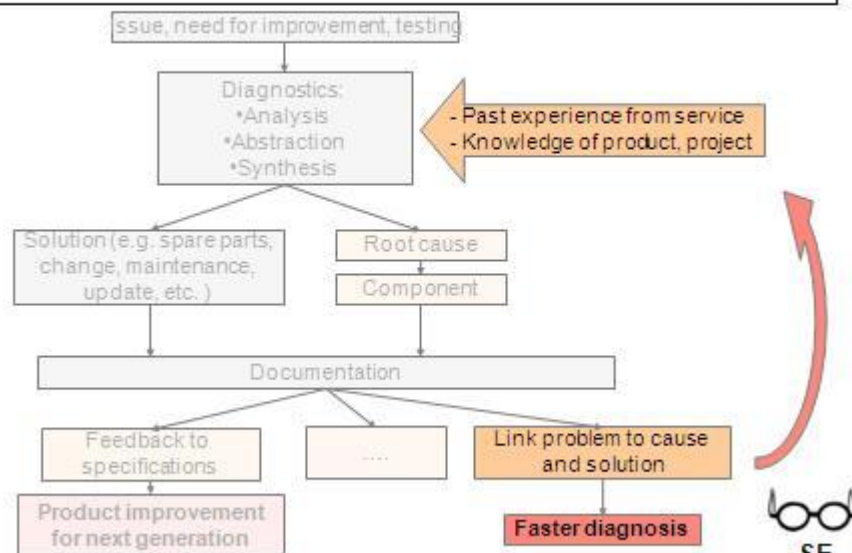


After investigation we find that mud and salt water impeded movement, extra greasing of the equipment is needed

How might we report the problem and the adopted solution?



## Reusing past experience during service

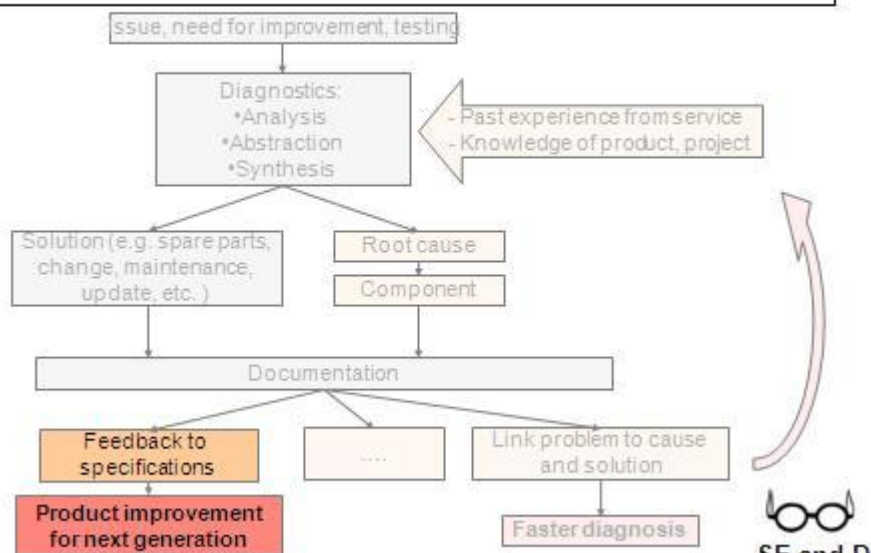


We realise that the same problem could occur in other rigs or other type of equipment

How might we avoid it occurring again in future and on-going projects?

- How might we transfer this information to others?
- How might we use this information?
- For which equipment is the information relevant?
- How might we monitor components to detect problem before the equipment goes in stand by?

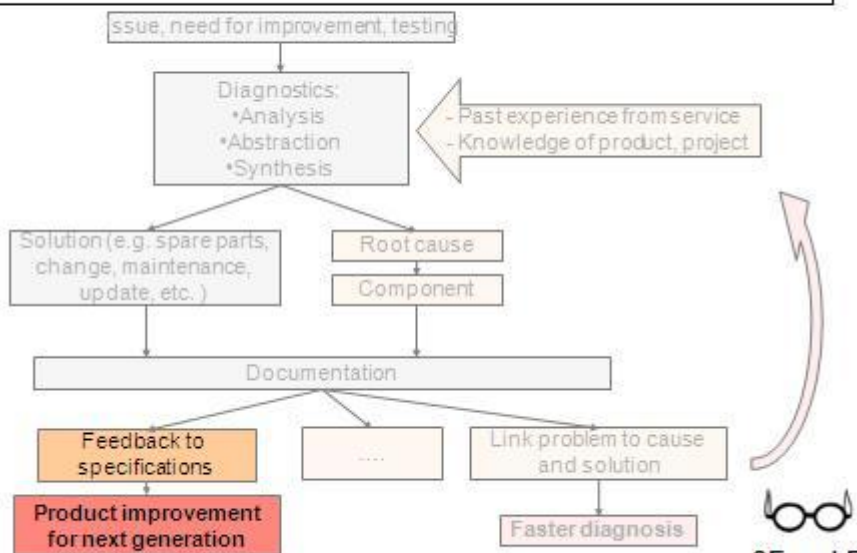
## Input for product improvement: problem



While diagnosing, we realise that current design makes lubrication of the equipment a time consuming activity due to lack of greasepoints

- How could the design be modified in order to facilitate the maintenance of the equipment?
- How could the design be modified in order to reduce the need of maintenance?
- How might designers take into account this information while designing the next generation of equipment?

## Input for product improvement: ideas





Some roughnecks have used non-greasable bushings but we (SE) saw that this does not help in certain weather conditions and think the presence of greasepoints could improve the machinery.

- How might designers want to be informed of ideas for improvement?
- How might we records input for improvement to use in future projects?
- How might we incorporate service knowledge into the requirements for the next generation of equipment?
- How might we record and compare the performances of alternative components?

## A.6 - Publications

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The research presented in this thesis was the subject of several papers; each paper was peer-reviewed. Here the papers are listed by topic:

### Comparison between oil and aerospace industry

- Co-authored paper: “*Handling of In-Service Support: Comparison of Two Case Studies from Complex Industries*” presented at Design 2010, International Design Conference, Dubrovnik - Croatia, May 17 - 20, 2010.

### Knowledge transfer mechanisms

- Co-authored paper “*Transfer of Service Knowledge: a Case from the Oil Industry*” presented at ICoRD, International Conference on Research into Design, Bangalore, January 7-9, 2009.
- Co-authored paper: “*Investigating Knowledge Transfer Mechanisms for Oil Rigs*” presented at ASME International Design Engineering Technical Conferences, San Diego, Cal., August 30-September 2, 2009.
- Co-authored paper: “*Knowledge Transfer between Service and Design Phases*” presented at the 17th International Conference on Engineering Design, ICED'09, Stanford University, Stanford, Cal., August 24-27, 2009.

### Engineering change management

- Co-authored paper: “*Engineering Changes from the Service Phase*” presented at ASME International Design Engineering Technical Conferences, August 3-6 2008, Brooklyn, New York.
- Co-authored paper: “*A comparative study of changes across the lifecycle of complex products in a variant and a customised industry*”, 2011, Journal of Engineering Design.

Additionally two journal articles were under review when this chapter was written:

- Extended version of the paper “*Transfer of Service Knowledge: a Case from the Oil Industry*” in review for publication in Research in Engineering Design.
- “*A Model for Reusing Service Knowledge Based on an Empirical Case*” in review for publication in Research in Engineering Design.

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Finally I would like to thank all the colleagues and friends that I met during the my PhD studies.

The reuse of knowledge generated during the different phases of a product's lifecycle is crucial for a company in order to achieve competitive advantage. This thesis investigates knowledge transfer within the service phase and between service and design phases through case studies from the oil industry. Knowledge generated during the service phase was analysed from the point of view of service engineers and engineering designers. Both were interested in knowledge about changes, issues and improvements generated during service; however, the study showed that knowledge transfer between the service and design departments was not systematic and consisted primarily of knowledge pushed by service engineers to engineering designers. The issues that posed a barrier to a systematic reuse of service knowledge were analysed and taken into consideration whilst developing a model to facilitate the reuse of the knowledge generated during the service phase.

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**DTU Management Engineering**  
**Department of Management Engineering**  
Technical University of Denmark

Produktionstorvet  
Building 424  
DK-2800 Kongens Lyngby  
Denmark  
Tel. + 45 45 25 48 00  
Fax +45 45 93 34 35

[www.man.dtu.dk](http://www.man.dtu.dk)